
We still believe in supersymmetry
You must be joking

SUSY Higgs Bosons: Reaching the LC Precision

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Sendai, 10/2019

1. The Quest for Precision

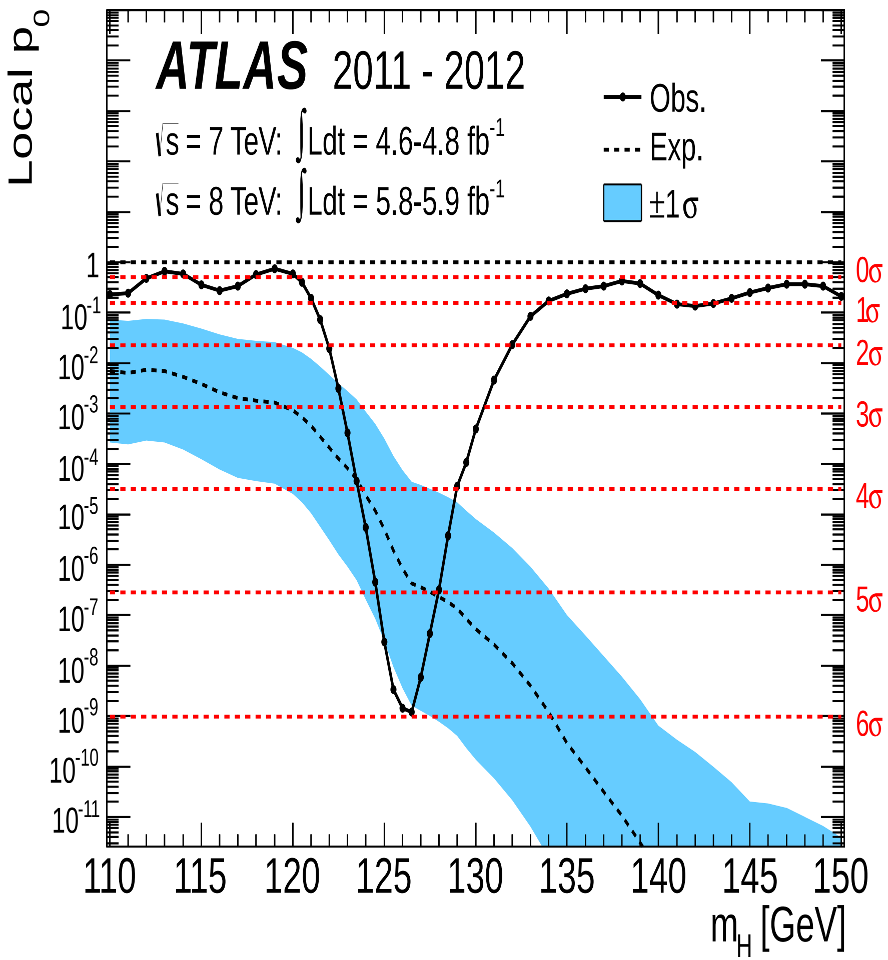
2. SUSY Higgs boson masses

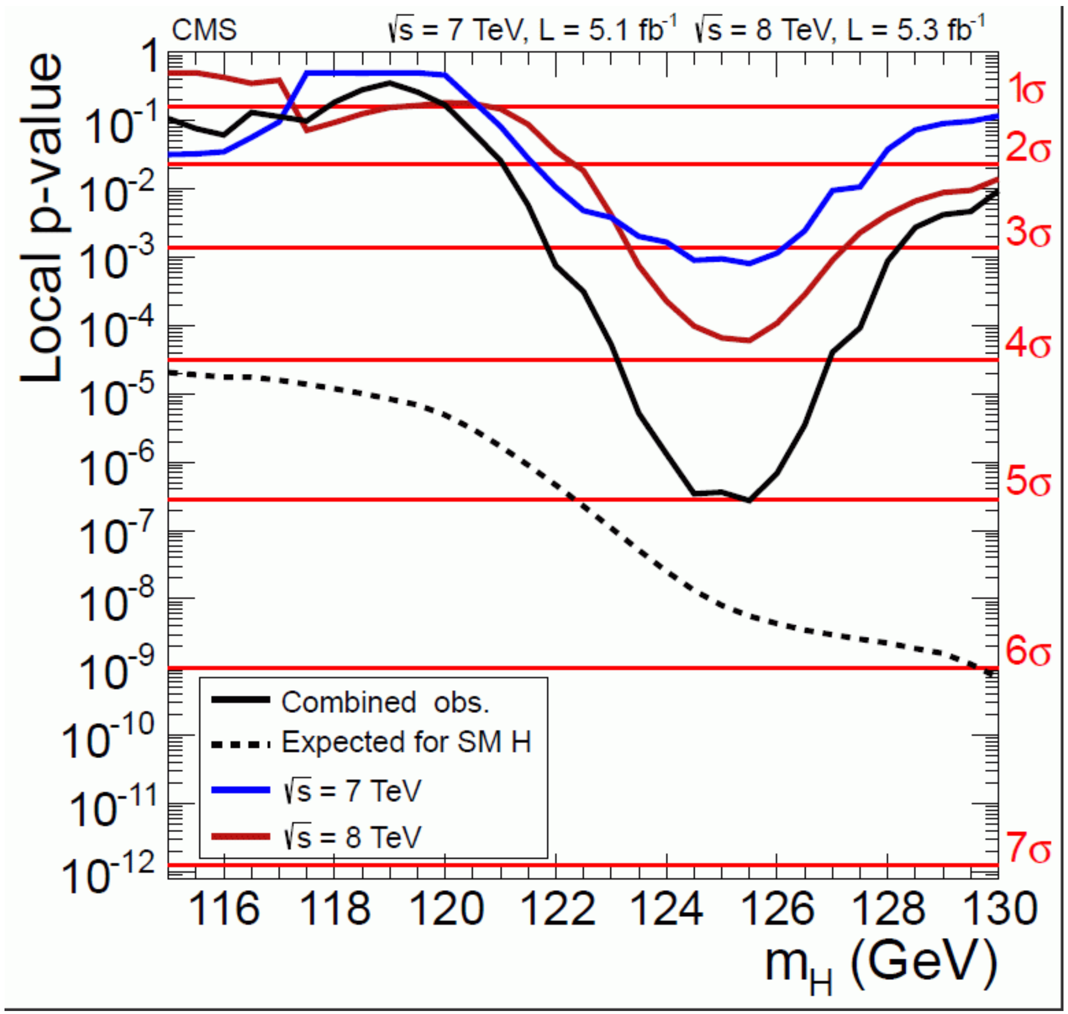
3. MSSM Higgs production cross sections

4. (N)MSSM Higgs decays

5. Conclusions

1. The Quest for Precision





⇒ clear discovery at $\sim$ 125 GeV!

⇒ can be interpreted as the light(/heavy) $\mathcal{CP}$-even MSSM Higgs

The Higgs mass accuracy: experiment vs. theory:

Experiment:

ATLAS: $M_h^{\text{exp}} = 125.36 \pm 0.37 \pm 0.18$ GeV

CMS: $M_h^{\text{exp}} = 125.03 \pm 0.27 \pm 0.15$ GeV

combined: $M_h^{\text{exp}} = 125.09 \pm 0.21 \pm 0.11$ GeV

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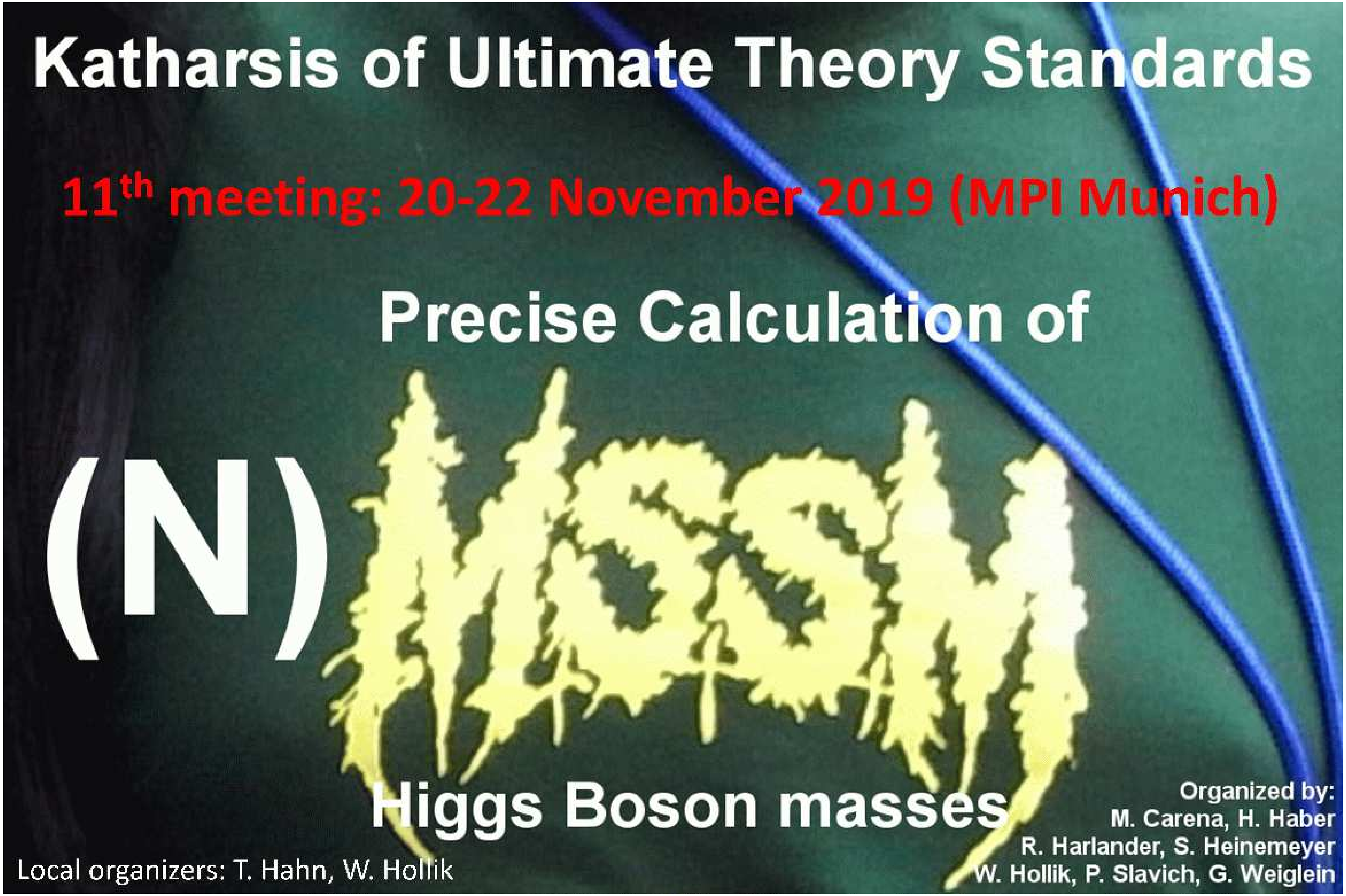
MSSM theory:

LHCHXSWG adopted FeynHiggs for the prediction of MSSM Higgs boson masses and mixings (considered to be the code containing the most complete implementation of higher-order corrections)

FeynHiggs: $\delta M_h^{\text{theo}} \sim 3$ GeV (now $1 - 2$ GeV?)

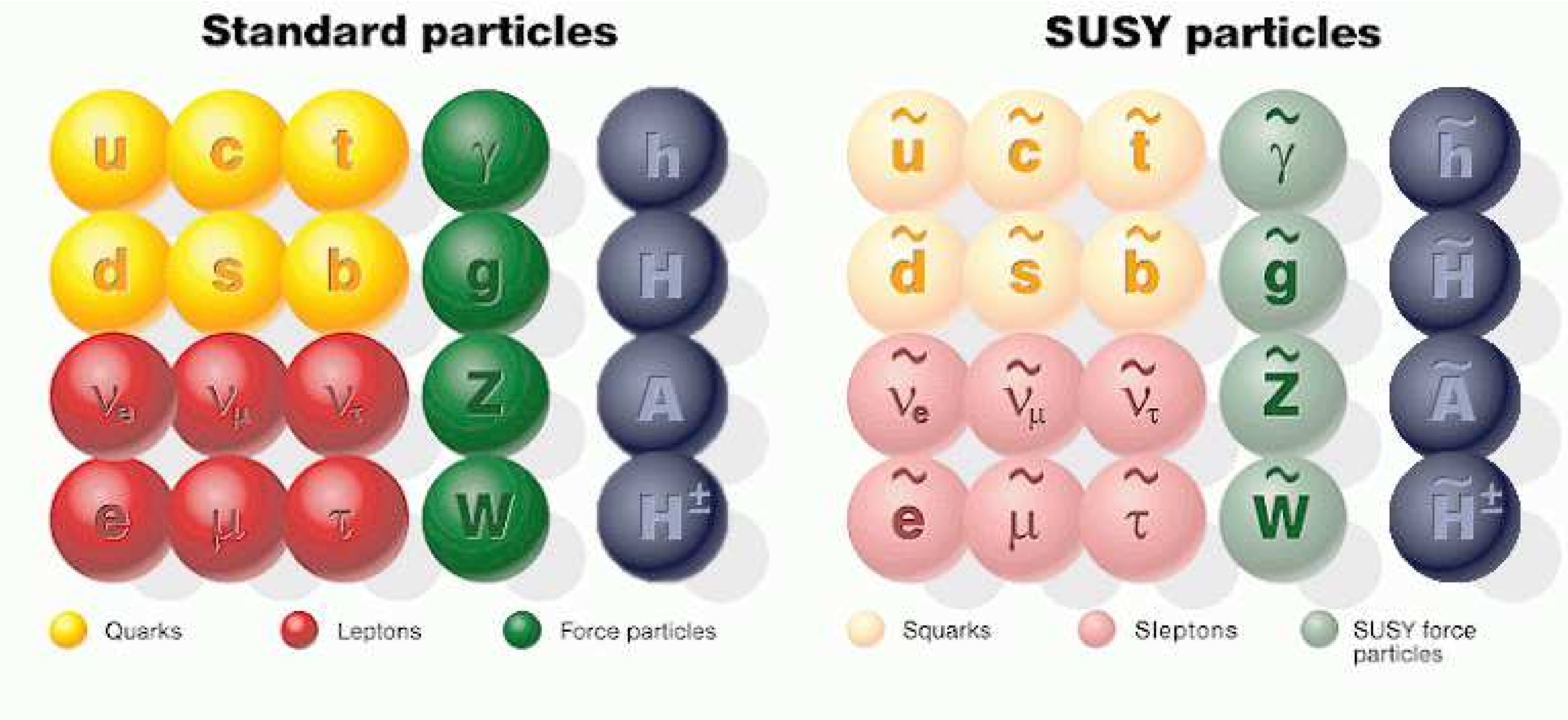
$\to$ rough estimate, FeynHiggs contains algorithm to evaluate uncertainty, depending on parameter point

Working group on M_h predictions: sites.google.com/site/kutsmh



The MSSM:

⇒ Superpartners for Standard Model particles



Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2 (\tan\beta + \cot\beta)$$

Enlarged Higgs sector: Two Higgs doublets with $\mathcal{CP}$ violation

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix} e^{i\xi}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$
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gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$

2 $\mathcal{CP}$-violating phases: ξ, arg(m_{12}) $\Rightarrow$ can be set/rotated to zero

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_{H^\pm}^2$$

Z_3 invariant NMSSM

MSSM Higgs sector: Two Higgs doublets

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$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$\begin{aligned} V &= (\tilde{m}_1^2 + |\mu \quad|^2) H_1 \bar{H}_1 + (\tilde{m}_2^2 + |\mu \quad|^2) H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\ &\quad + \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2 \end{aligned}$$

Z_3 invariant NMSSM

NMSSM Higgs sector: Two Higgs doublets + one Higgs singlet

$$
\begin{aligned}
H_1 &= \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix} \\
H_2 &= \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix} \\
S &= v_s + S_R + I S_I
\end{aligned}
$$

$$
\begin{aligned}
V = &\ (\tilde{m}_1^2 + |\cancel{\mu}\lambda S|^2) H_1 \bar{H}_1 + (\tilde{m}_2^2 + |\cancel{\mu}\lambda S|^2) H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\
&+ \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2 \\
&+ |\lambda(\epsilon_{ab} H_1^a H_2^b) + \kappa S^2|^2 + m_S^2 |S|^2 + (\lambda A_\lambda (\epsilon_{ab} H_1^a H_2^b) S + \frac{\kappa}{3} A_\kappa S^3 + \text{h.c.})
\end{aligned}
$$

Free parameters:

$$\lambda,\ \kappa,\ A_\kappa,\ M_{H^\pm},\ \tan\beta,\ \mu_{\text{eff}} = \lambda v_s$$

Higgs spectrum:

$$\begin{aligned} \mathcal{CP}\text{−even} &: h_1, h_2, h_3 \\ \mathcal{CP}\text{−odd} &: a_1, a_2 \\ \text{charged} &: H^+, H^- \\ \text{Goldstones} &: G^0, G^+, G^- \end{aligned}$$

Neutralinos:

$$\mu \to \mu_{\text{eff}}$$

compared to the MSSM: one singlino more

$$\to \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0$$

Mass of the lightest $\mathcal{CP}$-even Higgs:

$$m^2_{h,\text{tree,NMSSM}} = m^2_{h,\text{tree,MSSM}} + M_Z^2 \frac{\lambda^2}{g^2} \sin^2 2\beta$$

Mass of the $\mathcal{CP}$-odd Higgs:

$$\text{MSSM}: M_A^2 = -m_{12}^2(\tan\beta + \cot\beta) = \mu B(\tan\beta + \cot\beta)$$

$$\text{NMSSM}: \text{"}M_A^2\text{"} = \mu_{\text{eff}} B_{\text{eff}}(\tan\beta + \cot\beta)$$

$$\text{with } B_{\text{eff}} = A_\lambda + \kappa\, s,\ \mu_{\text{eff}} = \lambda\, s \qquad \Rightarrow \text{ one very light } a_1$$

Mass of the charged Higgs:

$$\text{MSSM}: M_{H^\pm}^2 = M_A^2 + M_W^2 = M_A^2 + \frac{1}{2} v^2 g^2$$

$$\text{NMSSM}: M_{H^\pm}^2 = M_A^2 + v^2 \left(\frac{g^2}{2} - \lambda^2\right)$$

Mass of the lightest $\mathcal{CP}$-even Higgs:

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$$\text{NMSSM}: M^2_{H^\pm} = M_A^2 + v^2 \left(\frac{g^2}{2} - \lambda^2\right)$$

$\Rightarrow M_{h_1}^{\text{MSSM,tree}} \le M_{h_1}^{\text{NMSSM,tree}}$, one light a_1, $M_{H^\pm}^{\text{MSSM,tree}} \ge M_{H^\pm}^{\text{NMSSM,tree}}$

Higgs coupling determination at e^+e^- collider:

recoil method: $e^+e^- \to ZH,\ Z \to e^+e^-,\ \mu^+\mu^-$

$\Rightarrow$ total measurement of Higgs production cross section

$\Rightarrow$ NO additional theoretical assumptions needed for absolute determination of partial widths

$\Rightarrow$ all observable channels can be measured with high accuracy

$\Rightarrow$ Cross section needed with high precision, better than $\sim 1\%$

Available: SM cross section predictions at the 1% accuracy level

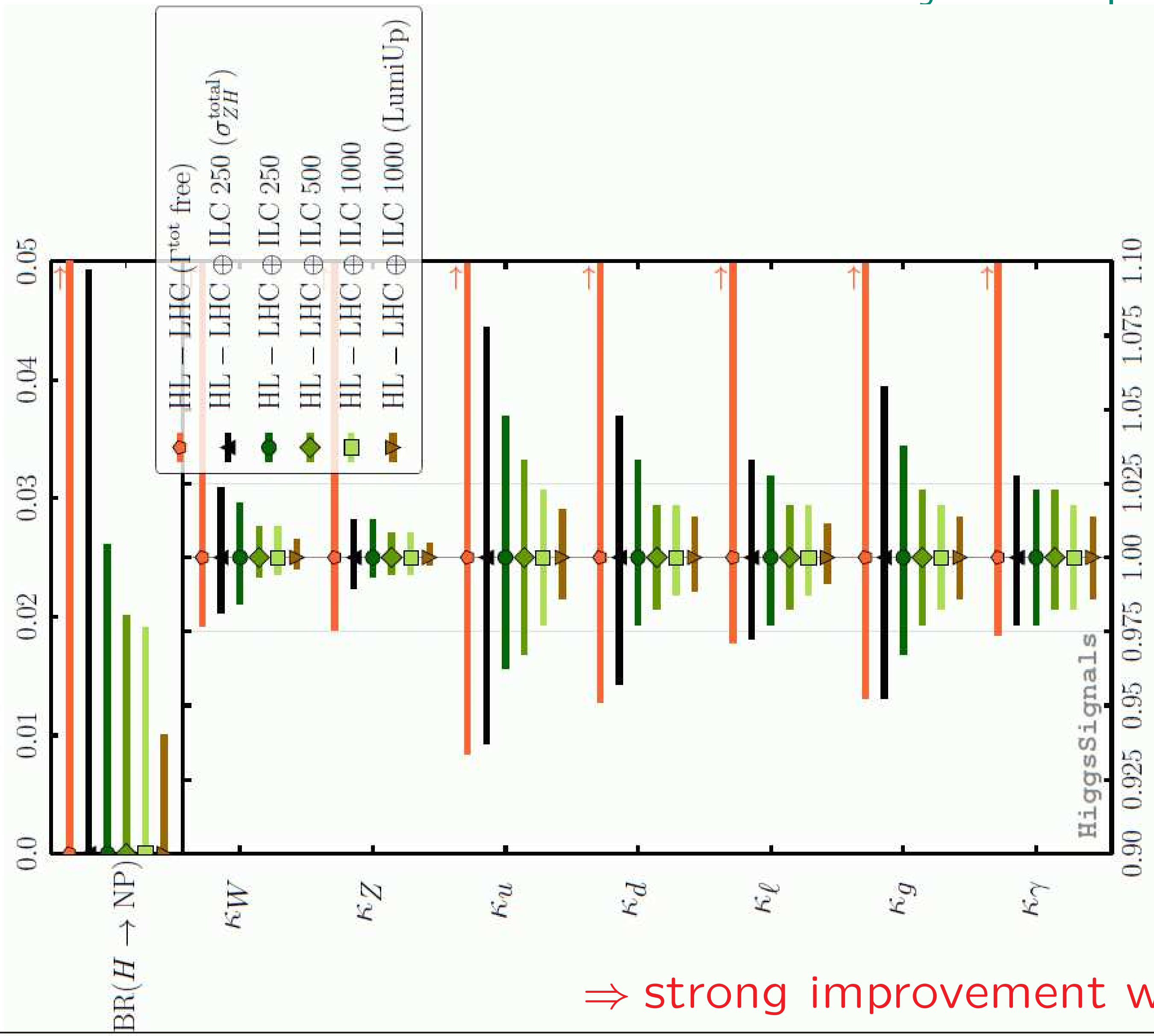
$\Rightarrow$ improvements necessary . . . full 2-loop calculations and more . . . ?!

$\Rightarrow$ What about the MSSM cross sections?

HL-LHC vs. ILC in the most general κ framework:

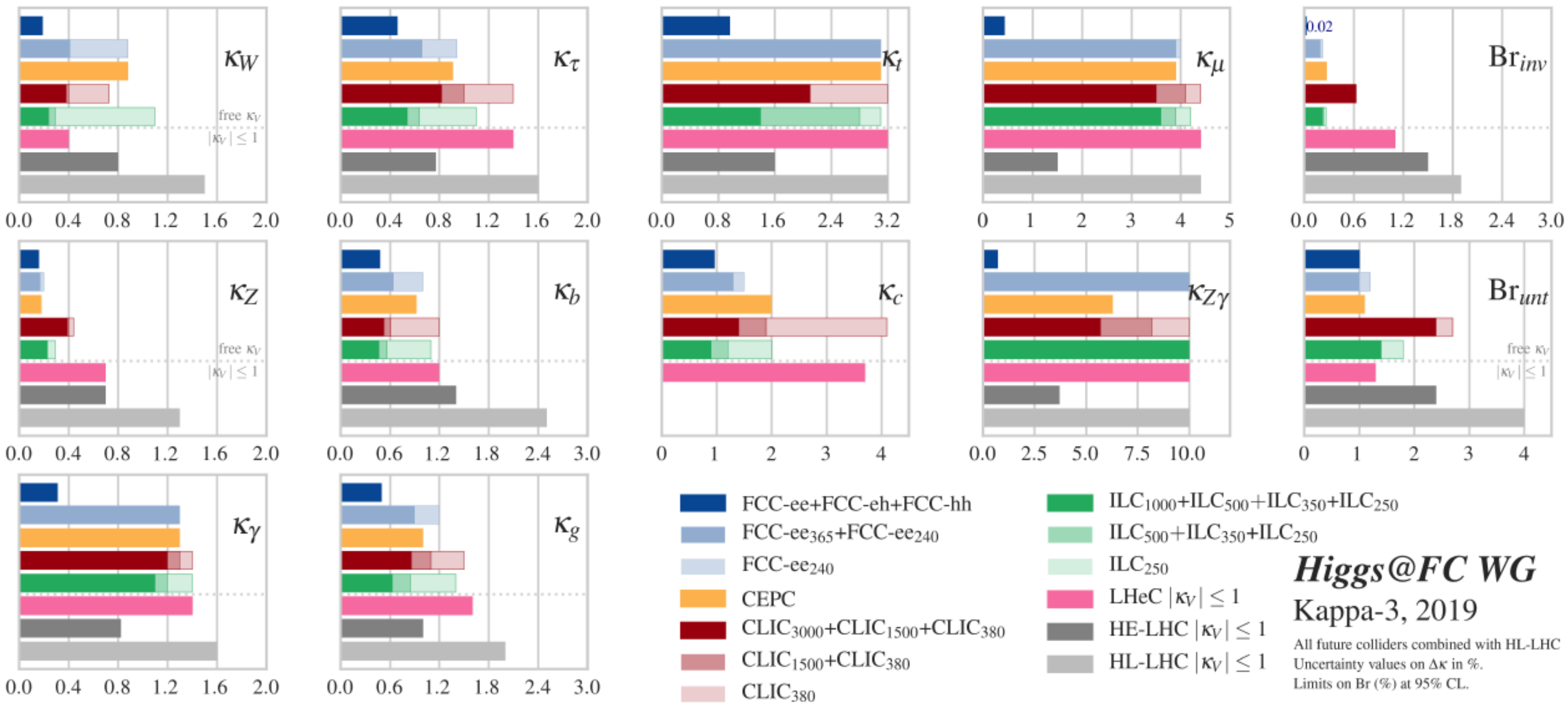
[*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14*]

no theory assumptions, full fit



⇒ strong improvement with the ILC

Future expectations for κ (kappa-3 framework)



$\Rightarrow$ very roughly similar results

$\Rightarrow$ FCC-hh/-he/-ee appears better

$\Rightarrow$ FCC-hh uses different theory assumptions, uncertainties $\lesssim 1\%$

$\Rightarrow$ also remember different time scales!

Needed for LHC/ILC/CLIC/... physics:

Precise and consistent prediction of

- Higgs boson masses
- Higgs boson mixings
- Higgs boson couplings
- Higgs boson production cross sections
- Higgs boson decay widths/branching ratios
- ...

$\Rightarrow$ (partially) provided by FeynHiggs

2. SUSY Higgs mass calculations

The "easy" case: MSSM:

Propagator/Mass matrix at tree-level:

$$\begin{pmatrix} q^2 - m_H^2 & 0 \\ 0 & q^2 - m_h^2 \end{pmatrix}$$

Propagator / mass matrix with higher-order corrections
($\to$ Feynman-diagrammatic approach):

$$M_{hH}^2(q^2) = \begin{pmatrix} q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\ & \\ \hat{\Sigma}_{hH}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

$\hat{\Sigma}_{ij}(q^2)$ $(i, j = h, H)$: renormalized Higgs self-energies

$\mathcal{CP}$-even fields can mix

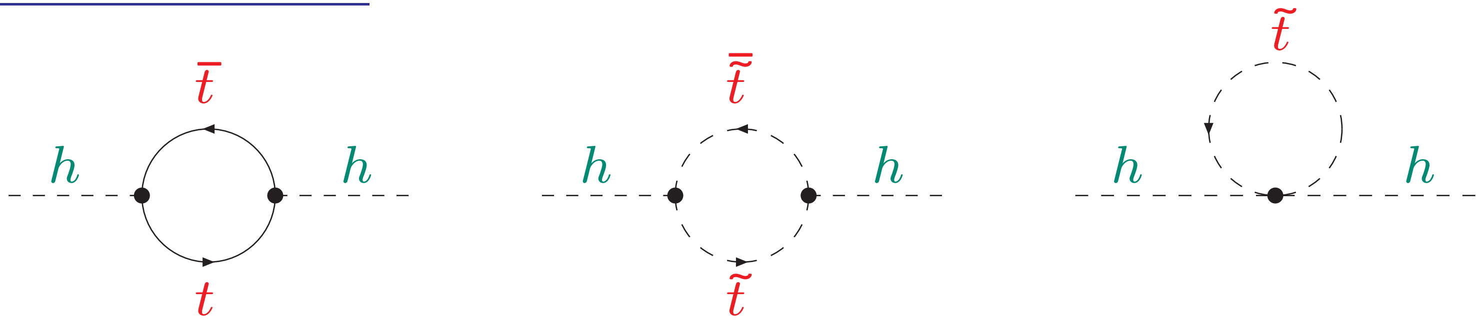
$\Rightarrow$ complex roots of $\det(M_{hH}^2(q^2))$: $\mathcal{M}_{h_i}^2 (i = 1, 2)$: $\mathcal{M}^2 = M^2 - iM\Gamma$

Calculation of renormalized Higgs boson self-energies:

$\hat{\Sigma}(q^2) = \hat{\Sigma}^{(1)}(q^2) + \hat{\Sigma}^{(2)}(q^2) + \ldots \;+\;$ log resum

Main contribution: $t/\tilde{t}$ sector (${\tilde{t}}$: scalar top, SUSY partner of the t)

Very leading 1-Loop:



Structure of higher-order corrections at one-loop:

$$\Delta M_h^2 \sim m_t^2 \alpha_t \left[L + L^0\right] \;, \quad L := \log\left(\frac{m_{\tilde{t}}}{m_t}\right)$$

Large $m_{\tilde{t}}$ $\Rightarrow$ large L $\Rightarrow$ resummation of logs necessary

Codes on the market:

1.) Fixed order codes: good for all scales low
- SuSpect
- SPheno/SARAH
- SoftSUSY/FlexibleSUSY
- H3m

2.) EFT codes (pure log resum): good for all scales high
- SusyHD
- MhEFT
- HSSUSY

3.) Hybrid codes: good always?!
- FeynHiggs
- FlexibleEFTHiggs
- SPheno/SARAH

Obviously: quality depends on the details implemented

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3.) Hybrid codes: good always?!
- FeynHiggs $\Leftarrow$ our code / best code :-)
- FlexibleEFTHiggs
- SPheno/SARAH

Obviously: quality depends on the details implemented

Possible & necessary refinements of the EFT calculation:

- Inclusion of EWino mass scale in RGE's
- Inclusion of gluino mass scale in RGE's
- Inclusion of EW effects in RGE's
- Inclusion of 3-loop RGEs plus 2-loop thresholds etc.
- "Two Higgs Doublet Model" below M_S
- Splitting in the scalar top sector
- ...

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- Inclusion of EWino mass scale in RGE's
  $\Rightarrow$ included into FeynHiggs

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- Inclusion of 3-loop RGEs plus 2-loop thresholds etc.
  $\Rightarrow$ included into FeynHiggs

- "Two Higgs Doublet Model" below M_S
  $\Rightarrow$ private version of FeynHiggs exists, other code: MhEFT

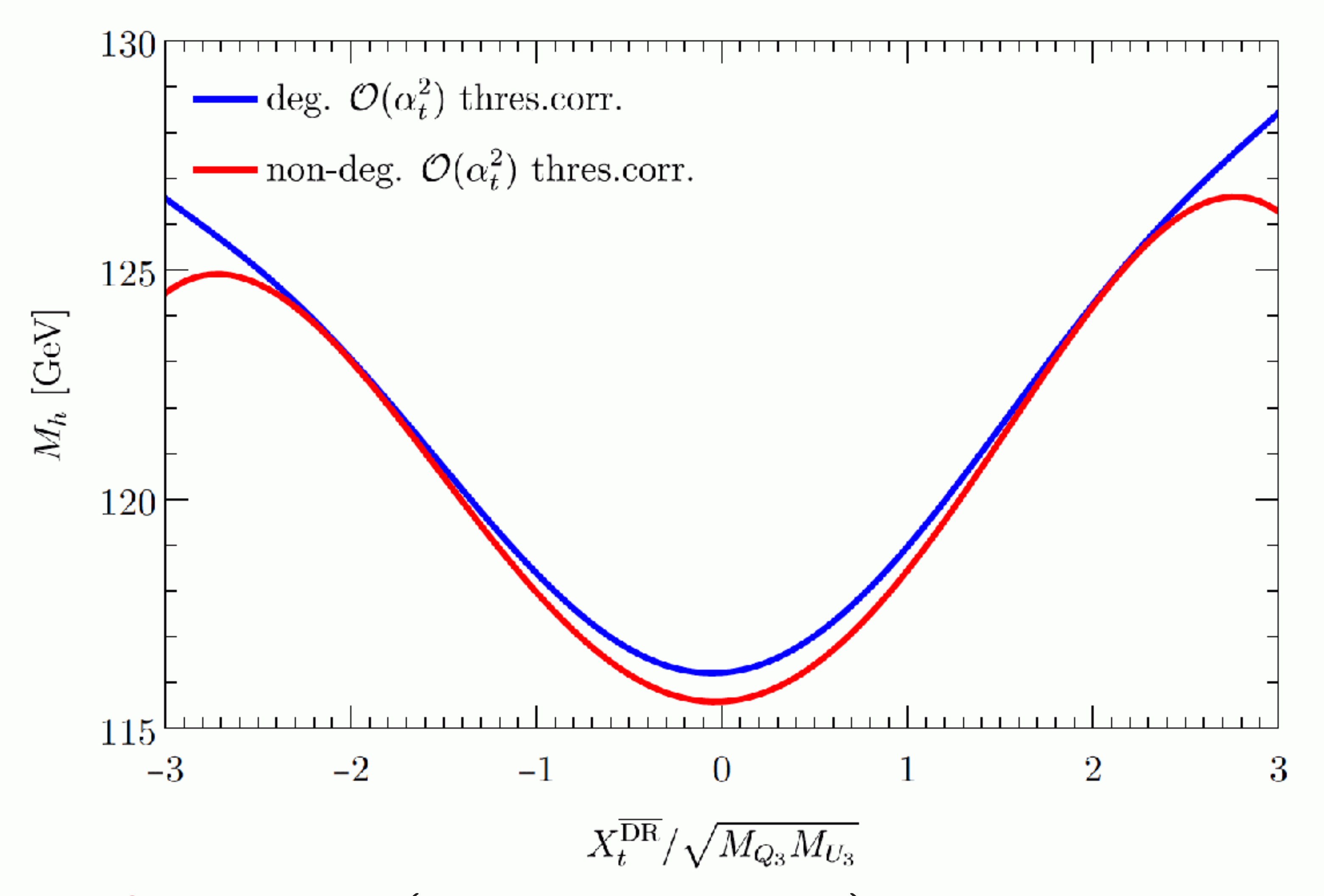
- Splitting in the scalar top sector
  $\Rightarrow$ future work

- ...

Impact of precise M_h calculation (I):

Impact of non-degenerate $\mathcal{O}\left(\alpha_t^2\right)$ threshold corr. in EFT part:

One scale M_{SUSY}, but large stop sector splitting, $\tan\beta = 10$:

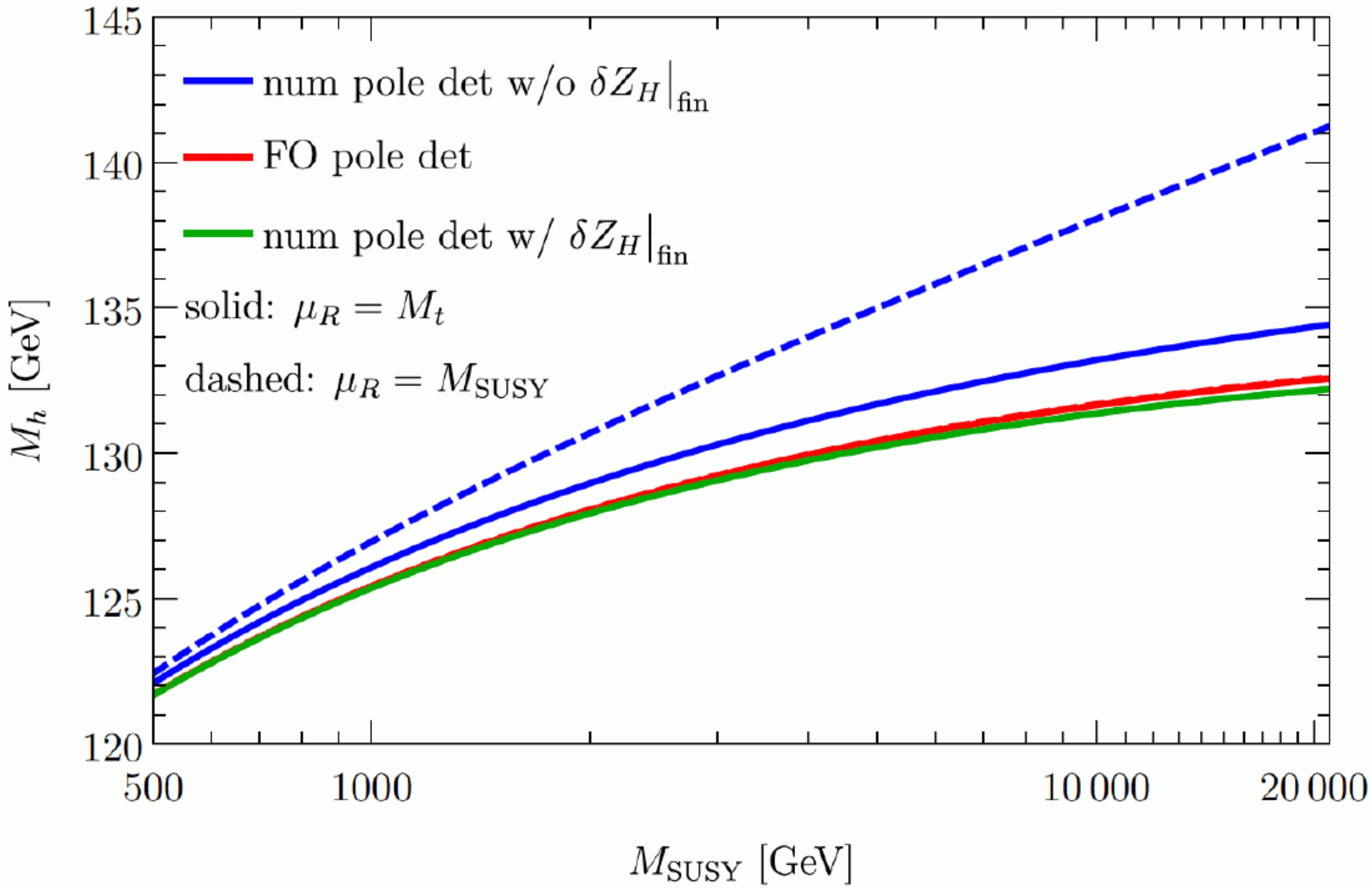


$\Rightarrow$ important for large X_t (more in a moment)

Impact of precise M_h calculation (II):

Impact of pole mass determination improvements:
(ask me details over coffee!)

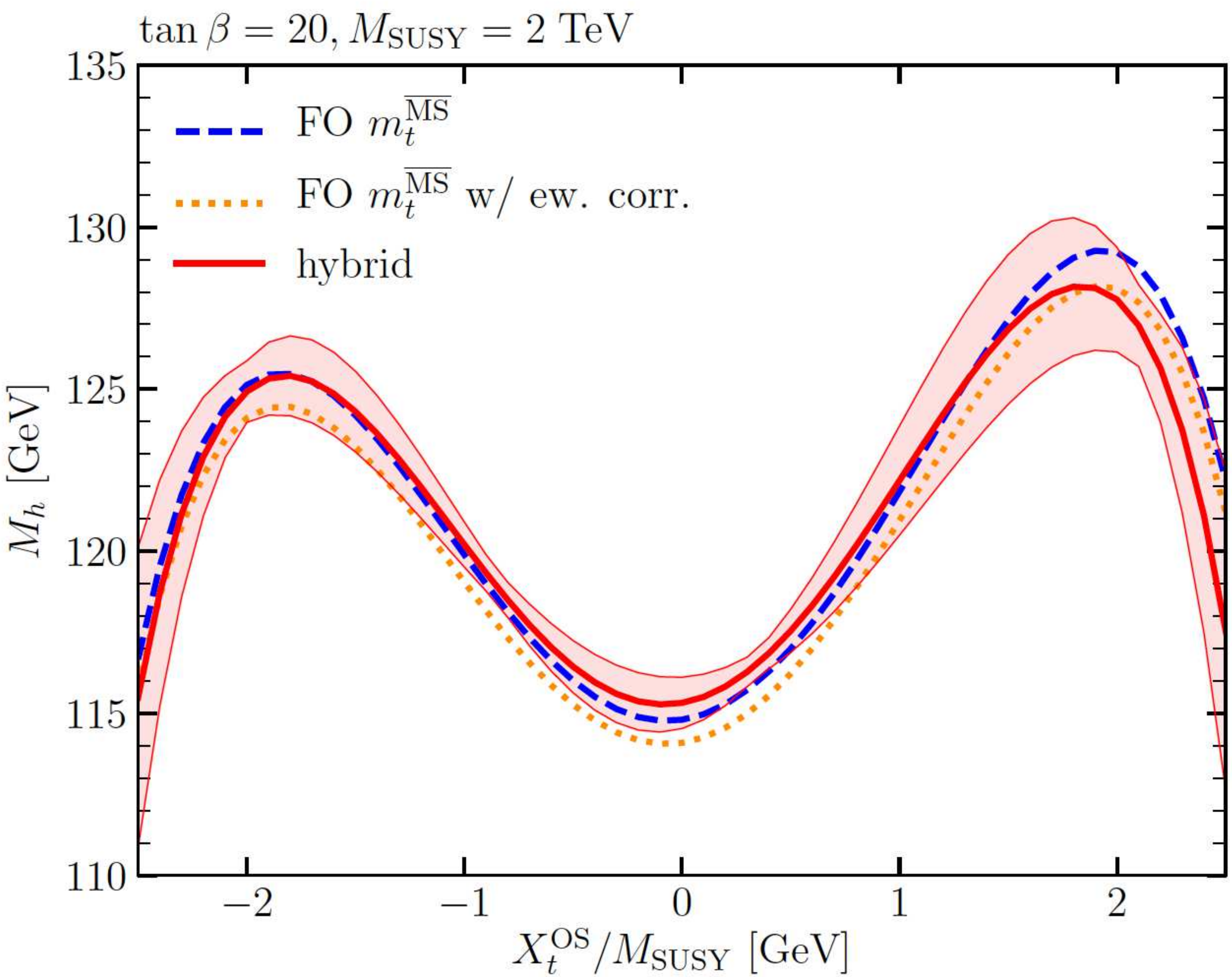
One scale M_{SUSY}, $\tan\beta = 10$:



$\Rightarrow$ calculation stabelized!

Improved uncertainty estimate:

[H. Bahl, S.H., W. Hollik, G. Weiglein '19 – PRELIMINARY]



⇒ reduced to 1-2 GeV (in simple single-scale scenario)

Going beyond the MSSM: the FeynHiggs Ansatz

(taken from talk by [*P. Drechsel*])

General idea: treat the MSSM part exactly as in the MSSM

- full inverse propagator in CP-even sector for mass determination

$$\Delta^{-1}\left(k^2\right) = \mathrm{i}\left[k^2\mathbb{1} - \underbrace{\mathcal{M}_{\phi\phi} + \hat{\Sigma}^{(1L)}_{\phi\phi}\left(k^2\right)}_{\text{NMSSM}} + \underbrace{\hat{\Sigma}^{(2L)}_{\phi\phi}\left(k^2 = 0\right)}_{\text{MSSM/FeynHiggs}}\right]$$

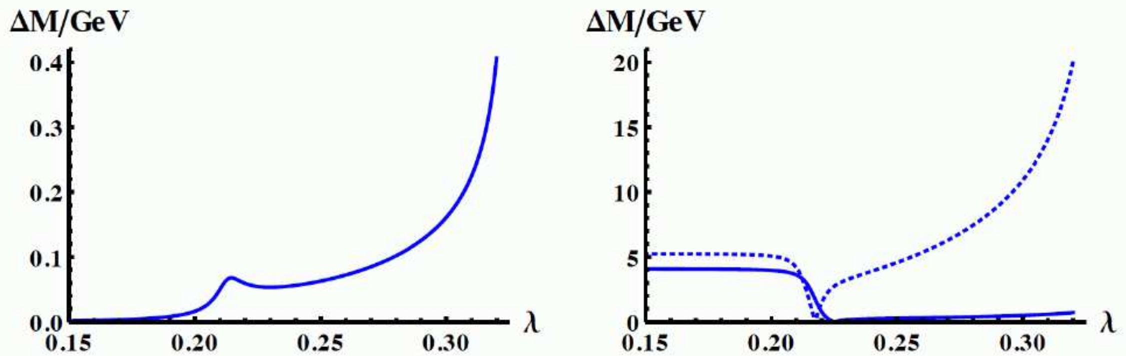
- included corrections from FeynHiggs at 2-loop order:
  - orders $\mathcal{O}\left(\alpha_s\alpha_t, \alpha_s\alpha_b, \alpha_t^2, \alpha_t\alpha_b\right)$
  - resummed large logarithms

⇒ any deviation from the MSSM can directly attributed to the extended model!

⇒ kind of obvious, but only FeynHiggs does it . . .

Lightest Mass @ 1-Loop Order: Sample Scenario

Absolute difference between different mass predictions



$$\Delta M = \left| m_{h_1}^{(Y_t)} - m_{h_1}^{(Y_t,\lambda)} \right| \qquad \Delta M = \left| m_{h_1}^{(Y_t,\lambda+\mathrm{H}+\mathrm{G})} - m_{h_1}^{(1\mathrm{L})} \right|$$

include Higgs- & gauge-sector

$\Longrightarrow$ influence of corrections beyond top/scalar top-sector is by far larger than those of the order $\mathcal{O}(Y_t\lambda, \lambda^2)$

$\Rightarrow$ we need two-loop calculations rather from the Higgs/gauge sector than from the genuine NMSSM $t/\tilde{t}$ sector!

$\Rightarrow$ those are not available and more complicated

$\Rightarrow$ NMSSM has intrinsically larger uncertainties than the MSSM

3. MSSM Higgs production cross sections

Neutral Higgs production:

$$e^+e^- \to h_i Z,\ h_i\gamma,\ h_i h_j,\ h_i\nu\bar{\nu},\ h_i e^+e^-,\ h_i t\bar{t},\ h_i b\bar{b},\ \ldots \qquad (i,j = 1,2,3)\,.$$

Now available in the cMSSM at the full one-loop level:

[*S.H., C. Schappacher '15*] [*F. Arco, S.H., C. Schappacher '18*]

$$\sigma(e^+e^- \to h_i h_j)$$

$$\sigma(e^+e^- \to h_i Z)$$

$$\sigma(e^+e^- \to h_i \gamma)$$

In the following:

few examples of each process, relevance of loop corrections

cMSSM parameters:

Table 2: MSSM default parameters for the numerical investigation; all parameters (except of t_β) are in GeV (calculated masses are rounded to 1 MeV). The values for the trilinear sfermion Higgs couplings, $A_{t,b,\tau}$ are chosen such that charge- and/or color-breaking minima are avoided [76], and $A_{b,\tau}$ are chosen to be real. It should be noted that for the first and second generation of sfermions we chose instead $A_f = 0$, $M_{\tilde{Q},\tilde{U},\tilde{D}} = 1500$ GeV and $M_{\tilde{L},\tilde{E}} = 500$ GeV.

Scen.	$\sqrt{s}$	t_β	μ	$M_{H^\pm}$	$M_{\tilde{Q},\tilde{U},\tilde{D}}$	$M_{\tilde{L},\tilde{E}}$	$\lvert A_{t,b,\tau}\rvert$	M_1	M_2	M_3
$\mathcal{S}$	1000	7	200	300	1000	500	$1500 + \mu/t_\beta$	100	200	1500

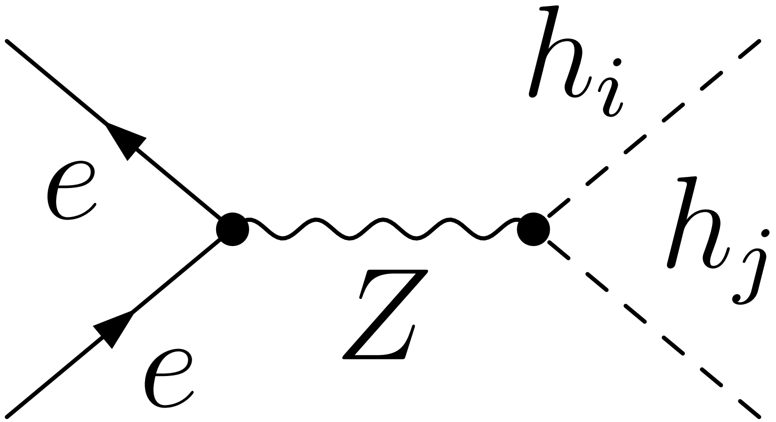
m_{h_1}	m_{h_2}	m_{h_3}
123.404	288.762	290.588

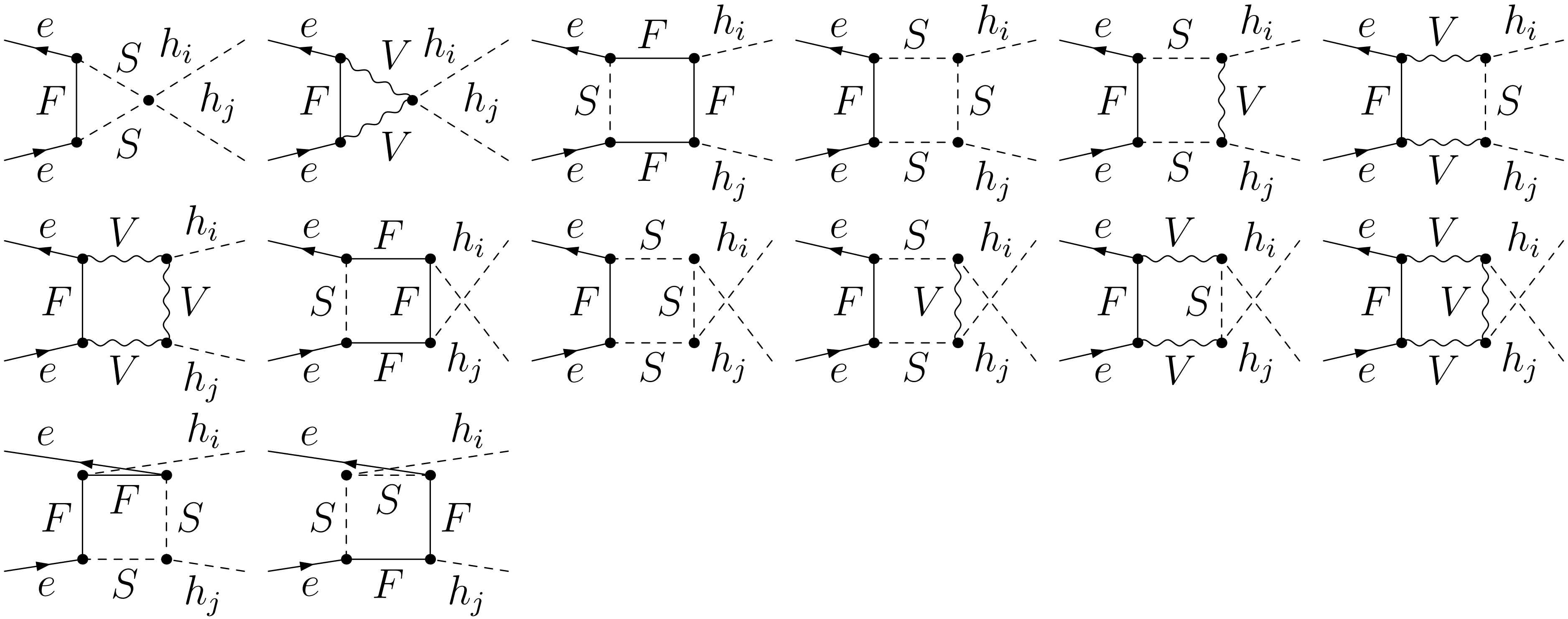
with $\sqrt{s}$, $M_{H^\pm}$, $\tan\beta$, ϕ_{A_t} varied

– Scenario chosen such that many processes are possible at the same time

– not chosen to maximize loop corrections

$e^+e^- \to h_i h_j$:


e
e
Z
h_i
h_j


e S h_i F h_j S e
e V h_i F h_j V e
e F h_i S F e F h_j
e S h_i F S e S h_j
e S h_i F V e S h_j
e V h_i F S e V h_j
e V h_i F V e V h_j
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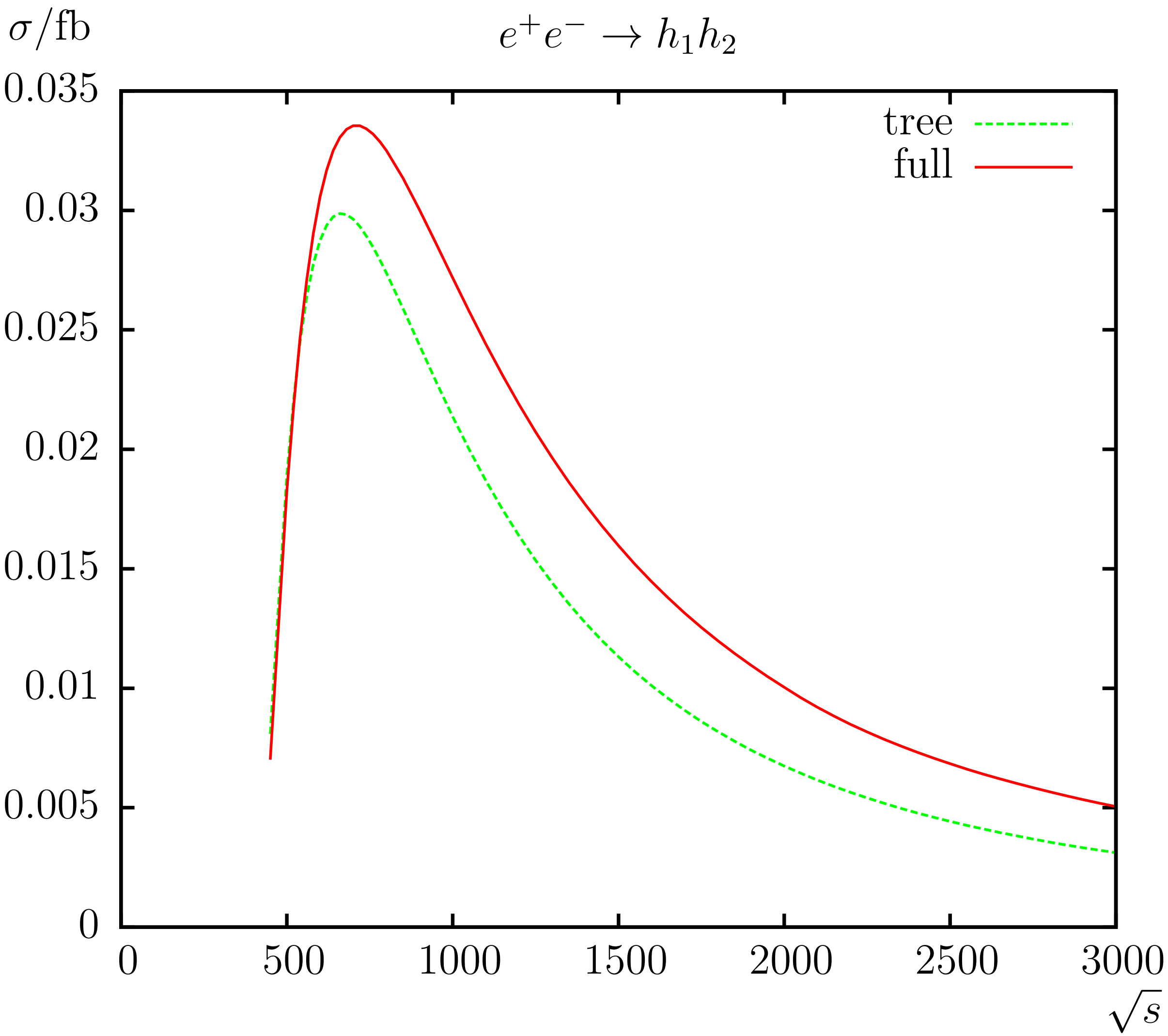
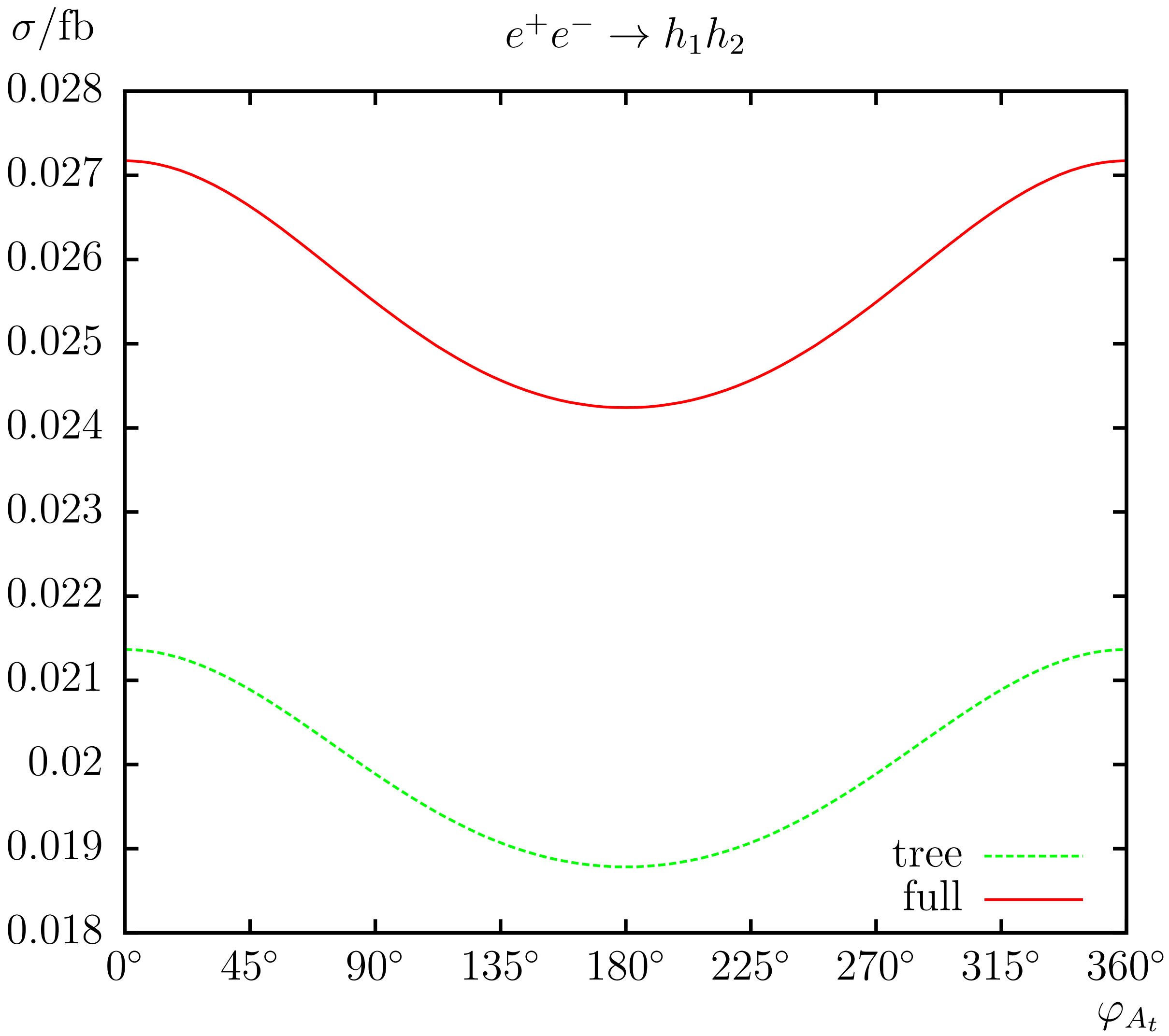
$e^+e^- \to h_1 h_2$:



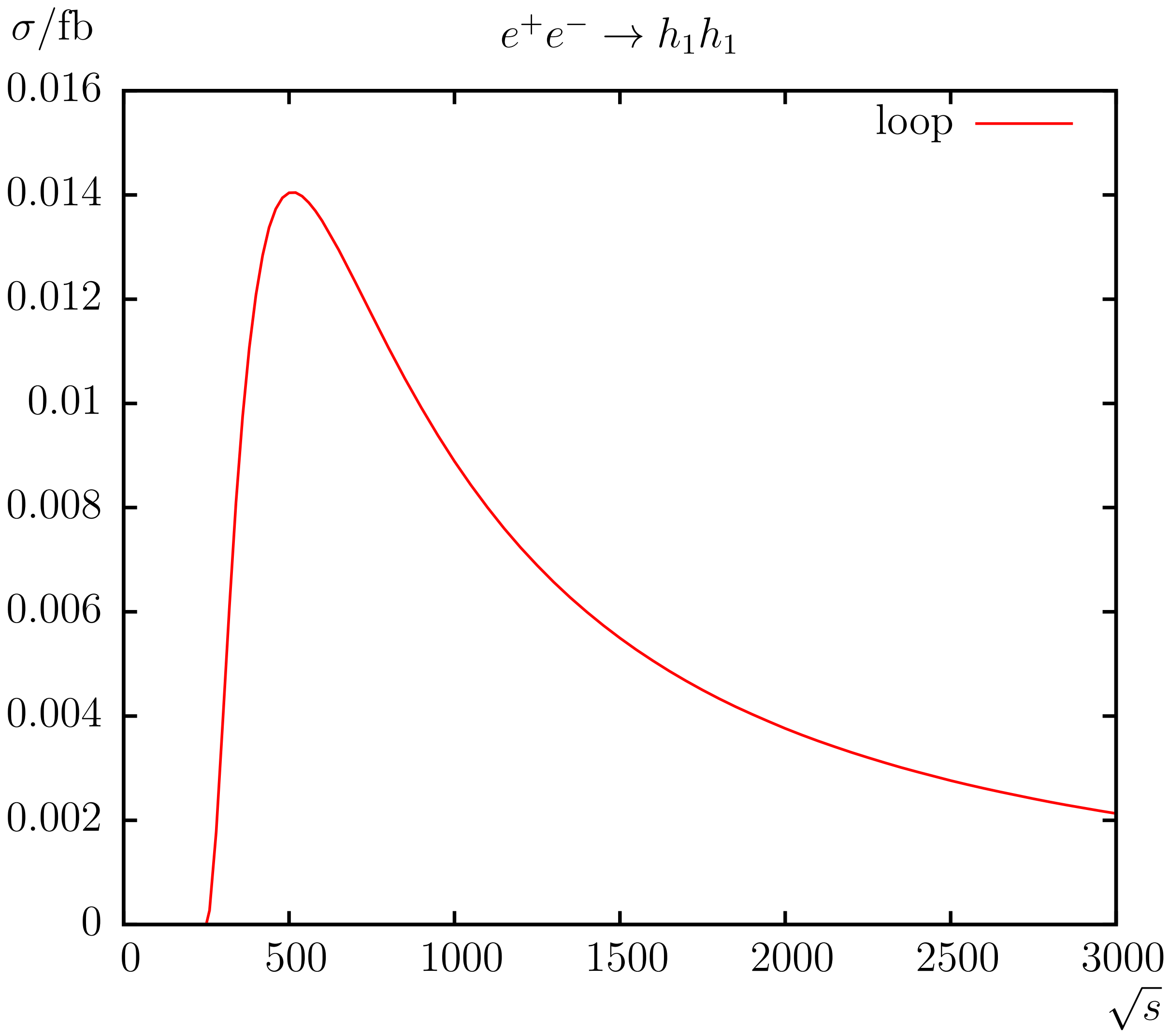
$\Rightarrow$ loop corrections crucial!

$e^+e^- \to h_1 h_2$:



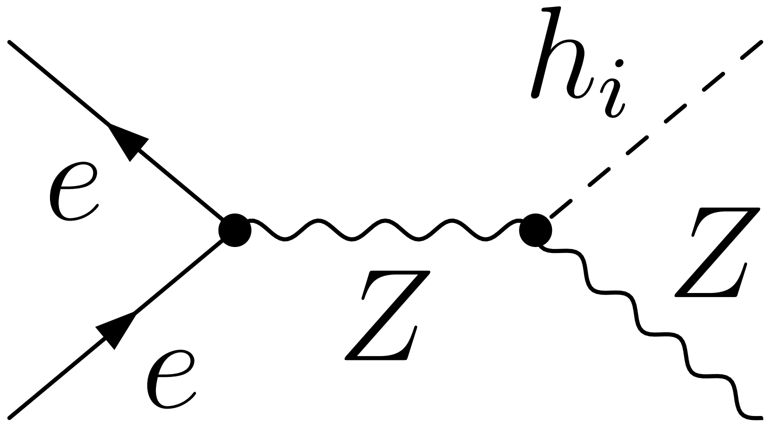
$\Rightarrow$ phase dependence more pronounced at loop-level

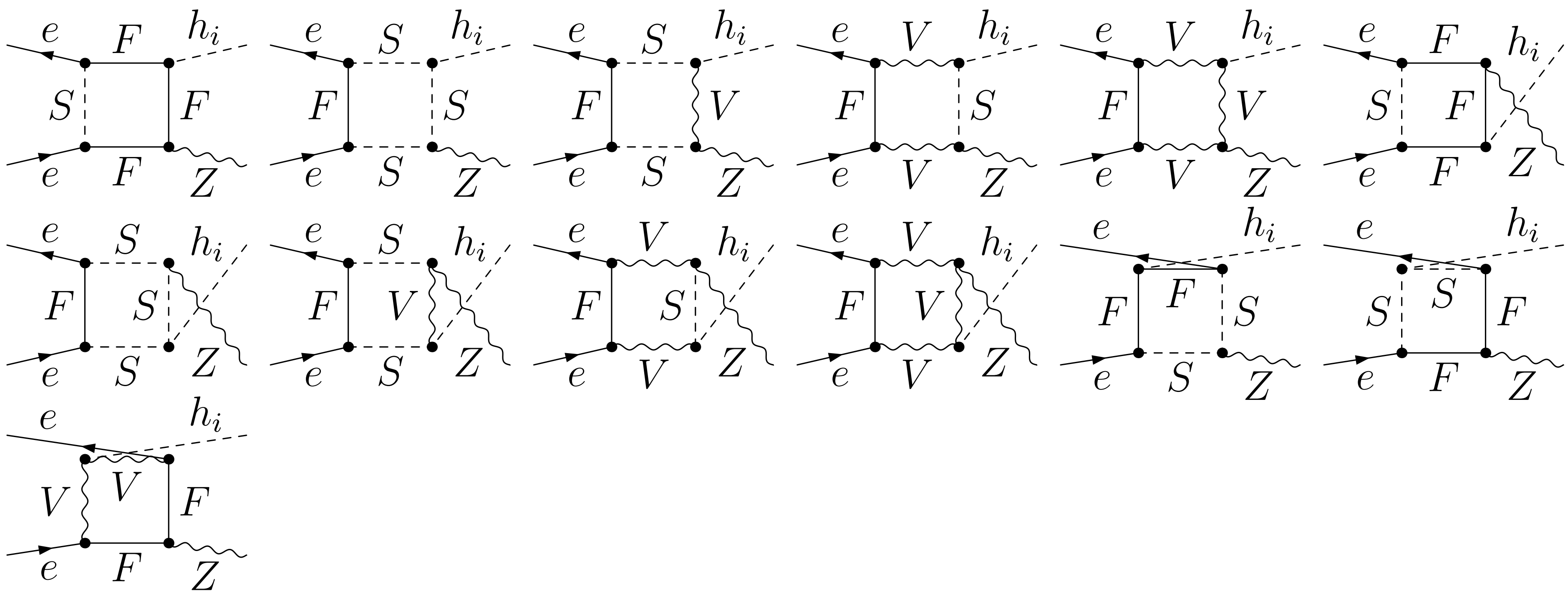
$e^+e^- \to h_1h_1$ (purely loop induced):



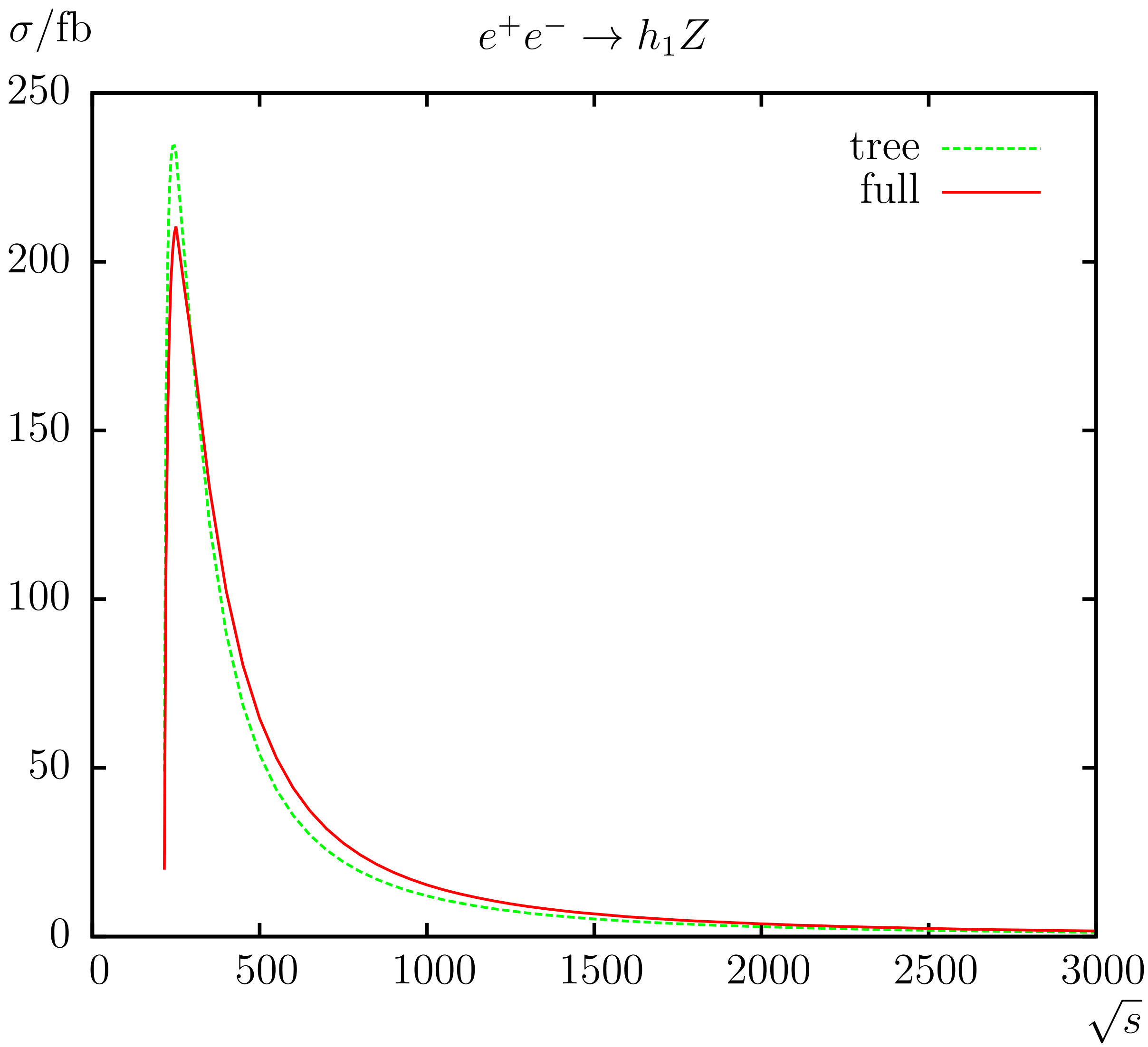
$\Rightarrow$ possibly observable!

$e^+e^- \to h_i Z$:



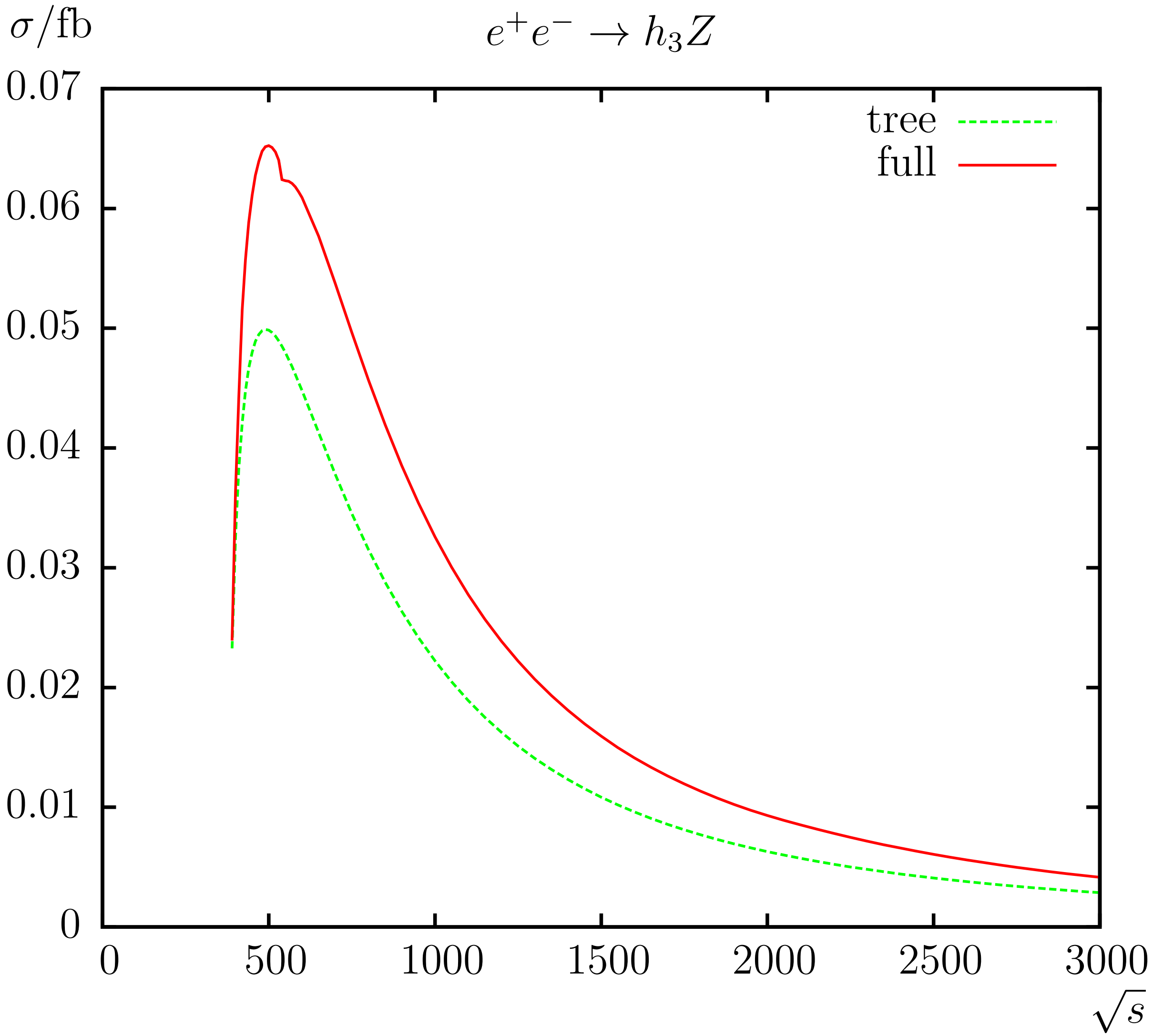


$e^+e^- \to h_1 Z$:



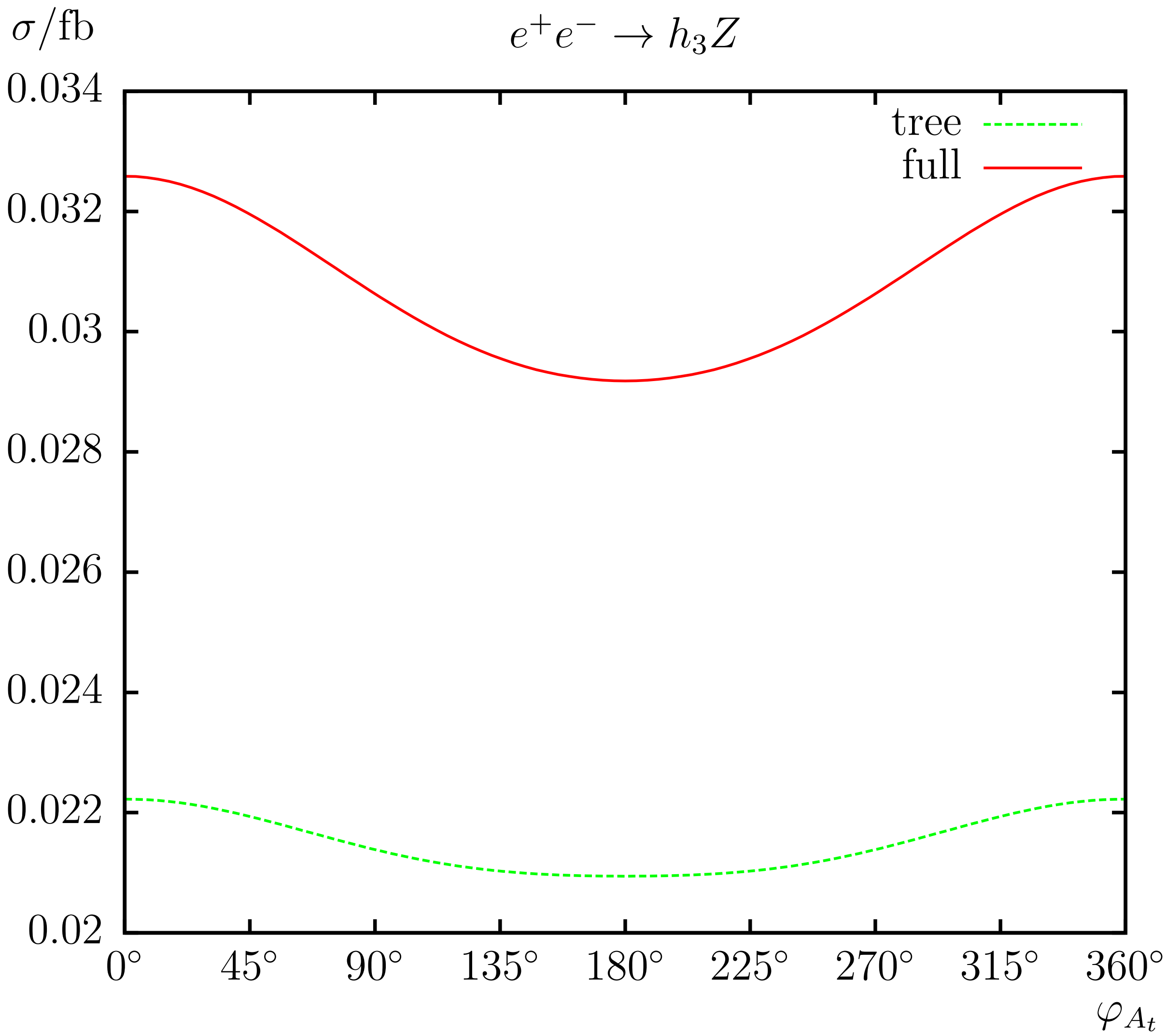
$\Rightarrow$ loop corrections crucial

$e^+e^- \to h_3 Z$:



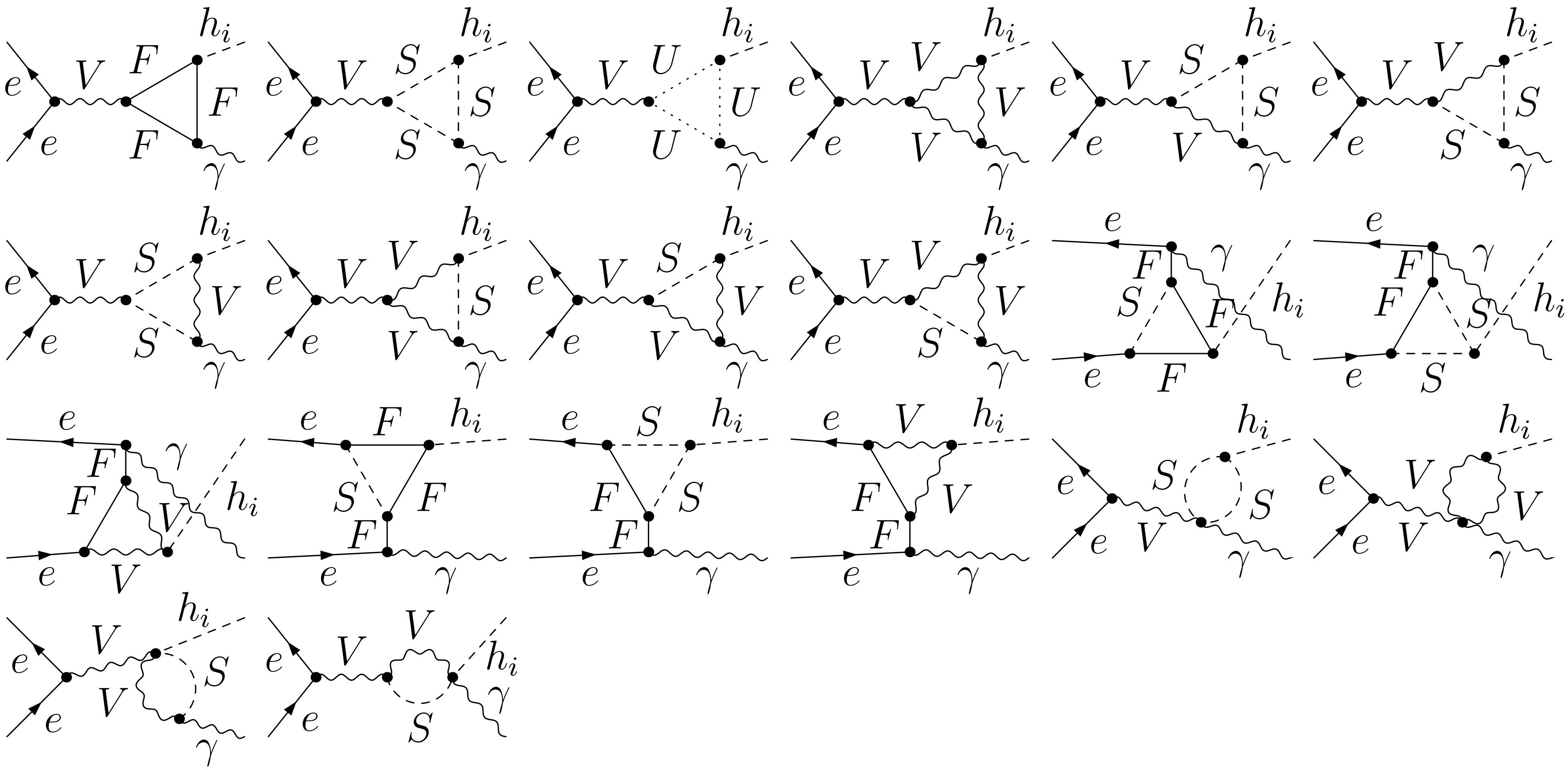
$\Rightarrow$ possibly observable, loop corrections crucial

$e^+e^- \to h_3 Z$:

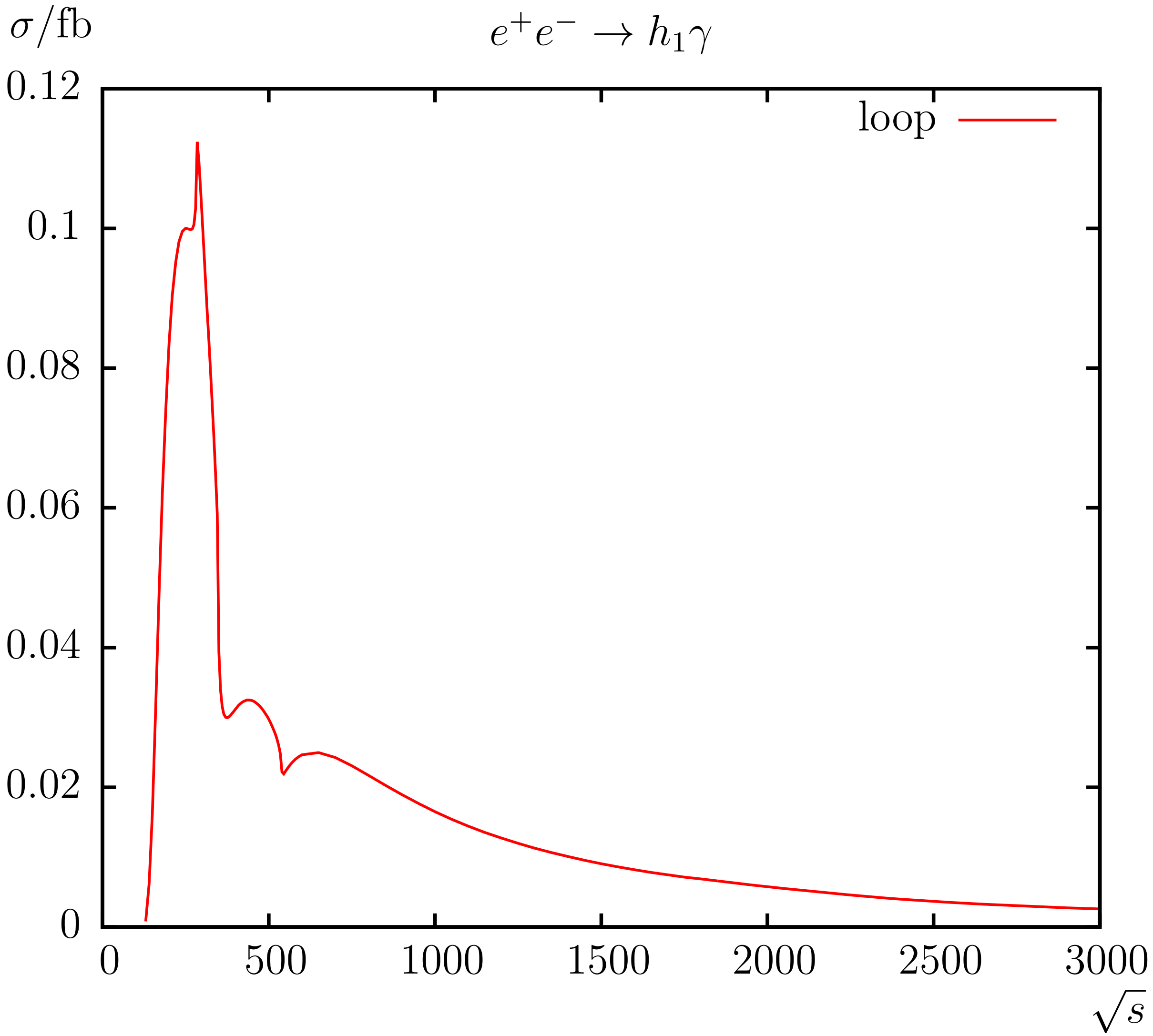


$\Rightarrow$ pronounced phase dependence at the loop level

$e^+e^- \to h_i\gamma$: purely loop-induced!

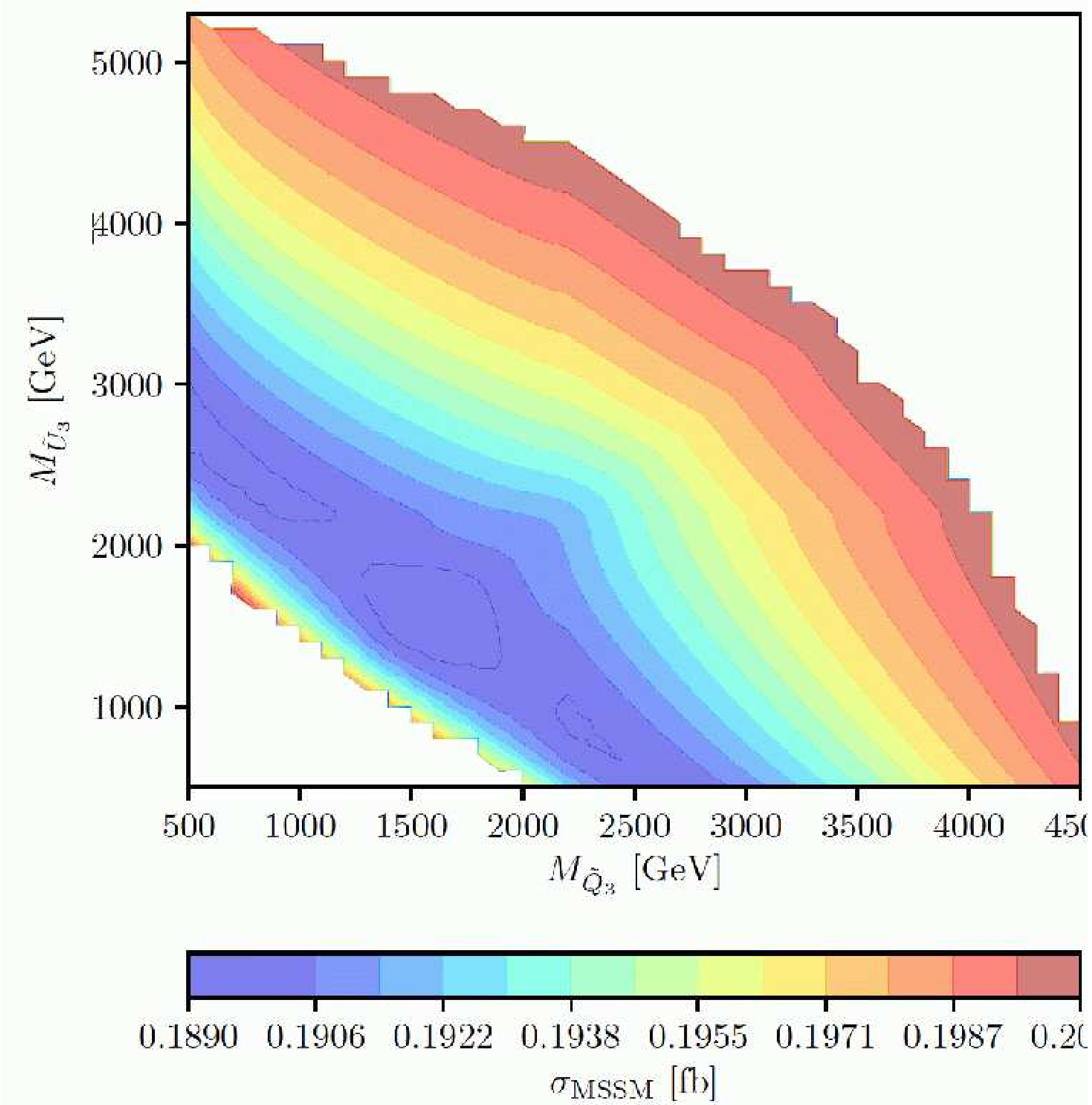


$e^+e^- \to h_1\gamma$ (purely loop induced):



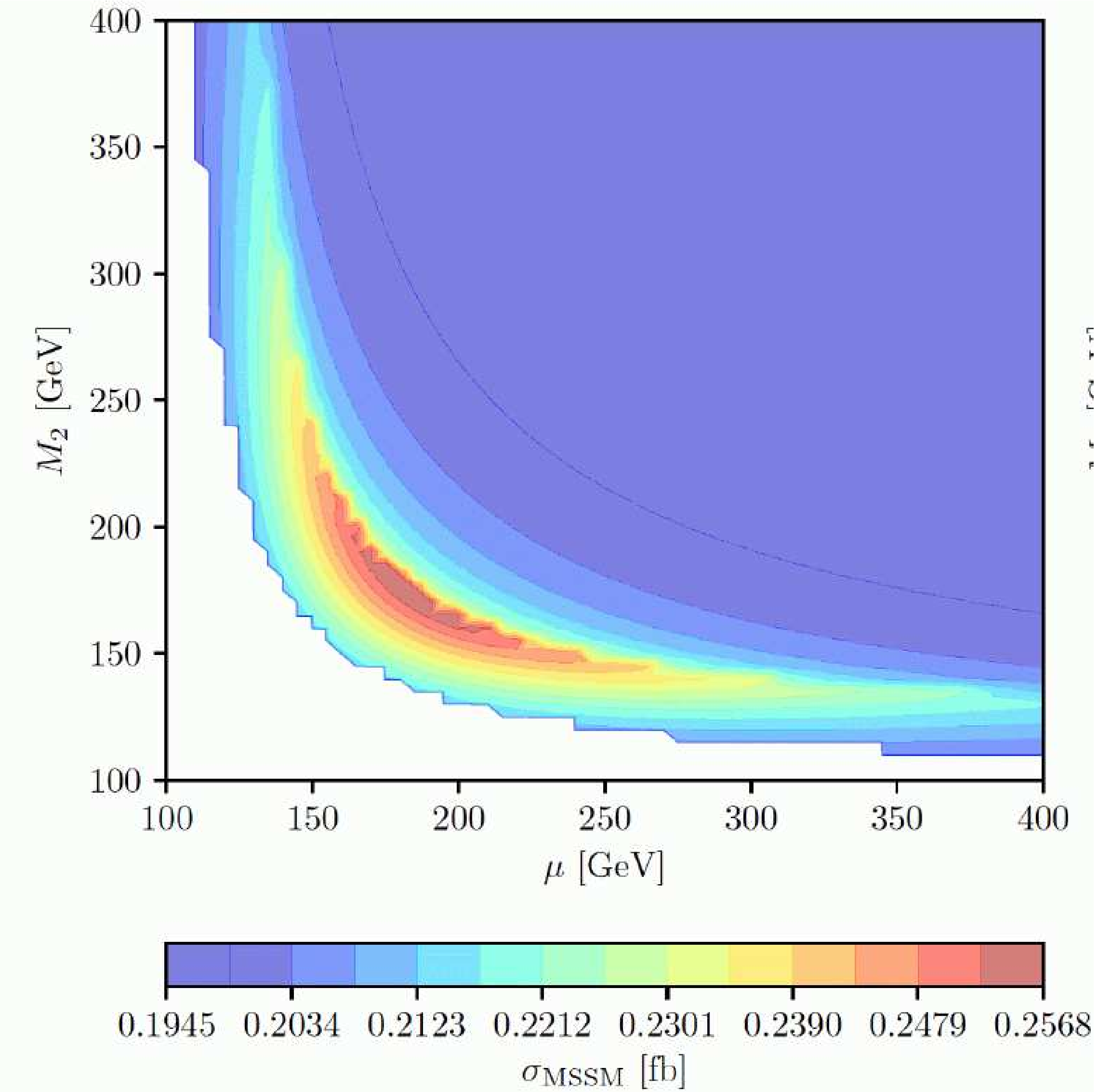
$\Rightarrow$ possibly observable!

$e^+e^- \to h_1\gamma$ (purely loop induced): [F. Arco, S.H., C. Schappacher '18]



⇒ relevant variation with scalar top sector

$e^+e^- \to h_1\gamma$ (purely loop induced): [F. Arco, S.H., C. Schappacher '18]



$\Rightarrow$ relevant variation with chargino sector

Charged MSSM Higgs Production at the LC

Charged Higgs production:

$$e^+e^- \to H^+H^-,\ H^\pm W^\mp,\ H^\pm e^\mp \nu,\ H^\pm tb, \ldots$$

Now available in the cMSSM at the full one-loop level:
[*S.H., C. Schappacher '17*]

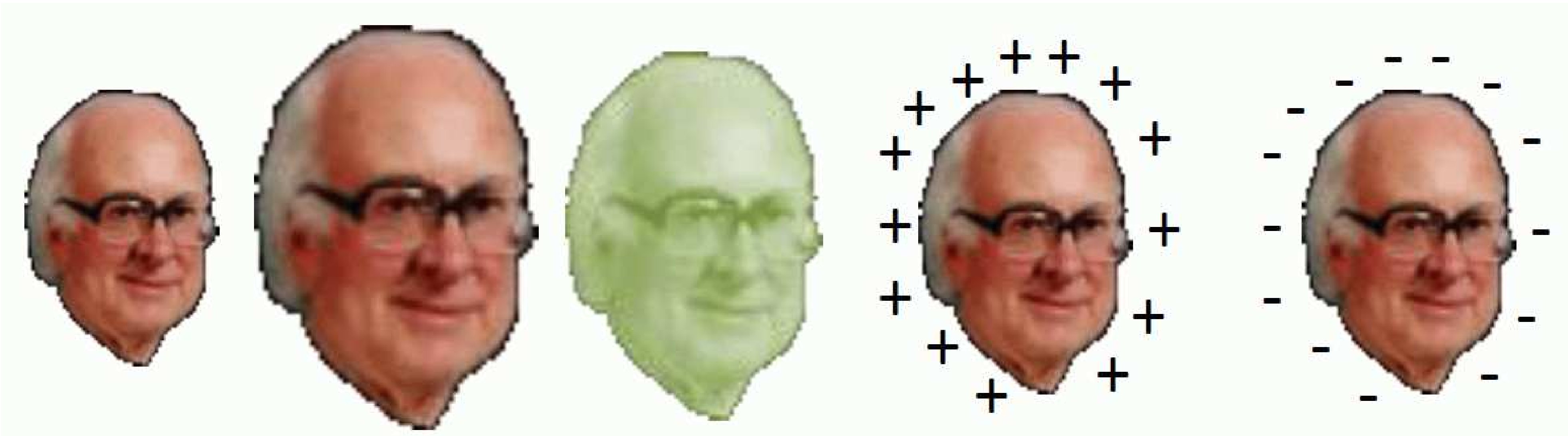
$$\sigma(e^+e^- \to H^+H^-)$$

$$\sigma(e^+e^- \to H^\pm W^\mp)$$

In the following:
few examples of each process, relevance of loop corrections

$\Rightarrow$ BACKUP

4. Higgs boson decays in the (N)MSSM



The FeynHiggs Ansatz for masses (taken from talk by [P. Drechsel])

General idea: treat the MSSM part exactly as in the MSSM

- full inverse propagator in CP-even sector for mass determination

$$\Delta^{-1}\left(k^2\right) = \mathrm{i}\left[k^2\mathbb{1} - \underbrace{\mathcal{M}_{\phi\phi} + \hat{\Sigma}^{(1\mathrm{L})}_{\phi\phi}\left(k^2\right)}_{\text{NMSSM}} + \underbrace{\hat{\Sigma}^{(2\mathrm{L})}_{\phi\phi}\left(k^2 = 0\right)}_{\text{MSSM/FeynHiggs}}\right]$$

- included corrections from FeynHiggs at 2-loop order:
  - orders $\mathcal{O}\left(\alpha_s\alpha_t, \alpha_s\alpha_b, \alpha_t^2, \alpha_t\alpha_b\right)$
  - resummed large logarithms

$\Rightarrow$ any deviation from the MSSM can directly attributed to the extended model!

$\Rightarrow$ kind of obvious, but only FeynHiggs does it . . .

The FeynHiggs Ansatz for masses (taken from talk by [P. Drechsel])

General idea: treat the MSSM part exactly as in the MSSM

- full inverse propagator in CP-even sector for mass determination

$$\Delta^{-1}\left(k^2\right) = \mathrm{i}\left[k^2\mathbb{1} - \underbrace{\mathcal{M}_{\phi\phi} + \hat{\Sigma}^{(1L)}_{\phi\phi}\left(k^2\right)}_{\text{NMSSM}} + \underbrace{\hat{\Sigma}^{(2L)}_{\phi\phi}\left(k^2=0\right)}_{\text{MSSM/FeynHiggs}}\right]$$

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  - resummed large logarithms

⇒ any deviation from the MSSM can directly attributed to the extended model!

⇒ kind of obvious, but only FeynHiggs does it . . .

⇒ **same Ansatz for Higgs decays!**

What is included in FeynHiggs (so far):

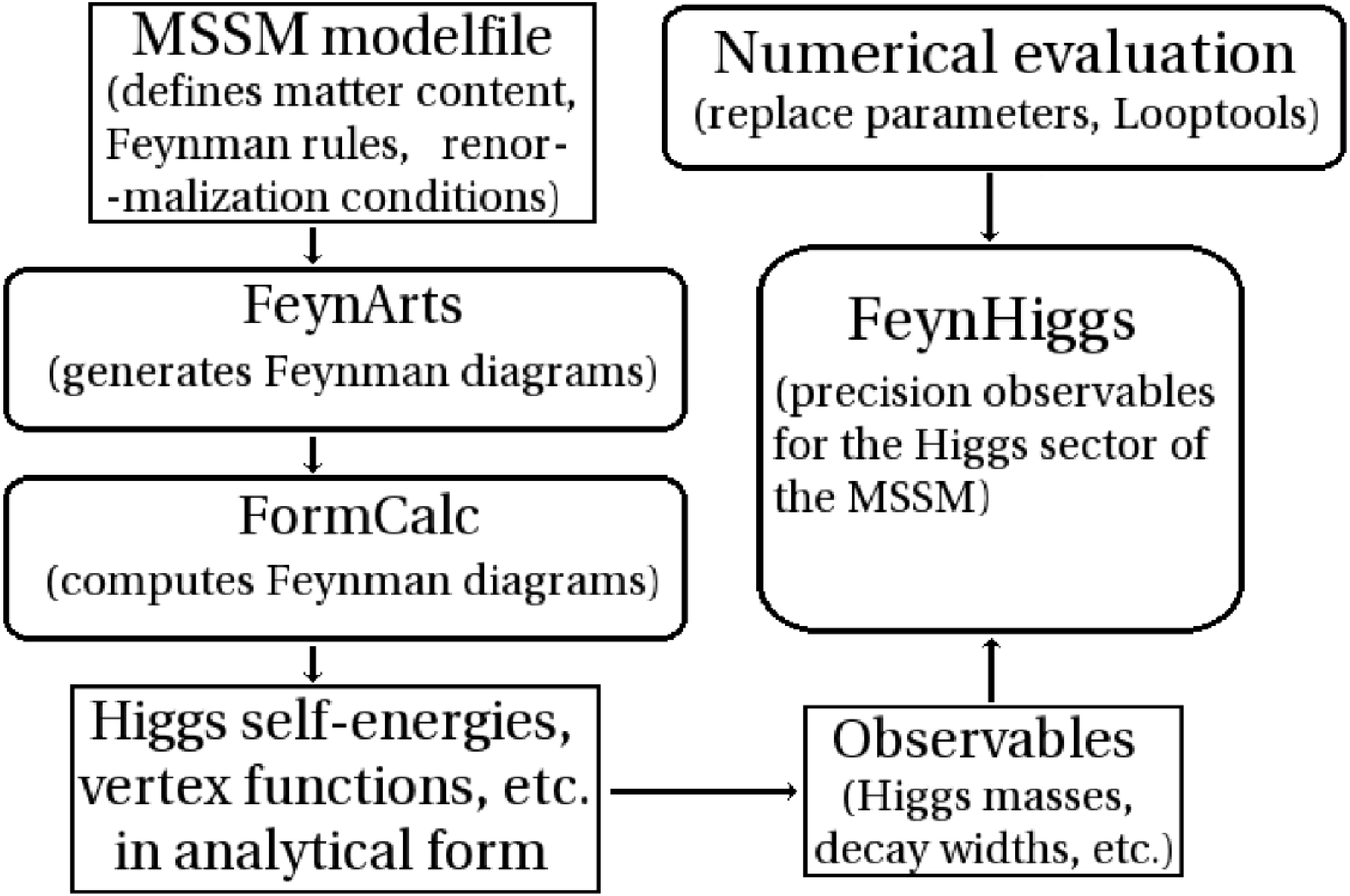
Evaluation of all MSSM Higgs boson masses and mixing angles

- $M_{h_1}, M_{h_2}, M_{h_3}, M_{H^\pm}$, α_{eff}, $\mathbf{Z}_{ij}$, $\mathbf{U}_{ij}$, . . . $\Rightarrow$ precision disussed before

Evaluation of all neutral MSSM Higgs boson decay channels (so far)

- total decay width Γ_{tot}
- BR$(h_i \to f\bar{f})$: decay to SM fermions: full 1L, running m_q at 3L, $\mathbf{Z}_{ij}$
- BR$(h_i \to Z^{(*)}Z^{(*)}, W^{(*)}W^{(*)})$: decay to massive SM gauge bosons: Prophecy4f $\oplus$ coupling factors, $\mathbf{U}_{ij}$
- BR$(h_i \to \gamma\gamma, gg)$: decay to massless SM gauge bosons: NLO QCD, gg: NNLO, NNLL from SM, $\mathbf{U}_{ij}$
- BR$(h_i \to h_j Z^{(*)}, h_j h_k)$: decay to gauge and Higgs bosons: $h_j Z^{(*)}$: $\mathbf{U}_{ij}$, $h_j h_k$: full 1L, log-resum, $\mathbf{Z}_{ij}$
- BR$(h_i \to \tilde{f}_i \tilde{f}_j)$: decay to sfermions: $\mathbf{U}_{ij}$
- BR$(h_i \to \tilde{\chi}^\pm_i \tilde{\chi}^\mp_j, \tilde{\chi}^0_i \tilde{\chi}^0_j)$: decay to charginos, neutralinos: $\mathbf{U}_{ij}$

FeynHiggs "workflow" :



Idea for this work:

[*slide from F. Domingo*]

- Renormalization of the CP-conserving Higgs-sector *[Drechsel, Galeta, Heinemeyer, Weiglein, (2016)]*;
- CP-violating NMSSM, on-shell neutral Higgs *[Drechsel, F.D., Paßehr (2017)]*;
- Neutral Higgs decays into SM particles at full one-loop order *[F.D., Heinemeyer, Paßehr, Weiglein, (2018)]*;
- Higgs-to-Higgs + Higgs-to-SUSY on-going. . .
- Inclusion within FeynHiggs in an unforseeable future. . .

Learn from MSSM and adapt to the NMSSM.
+ Re-juvenate MSSM from NMSSM.

In the future: **FeynHiggs 3.0**

$\Rightarrow$ few numerical examples for the Higgs decays

Overall (N)MSSM Higgs decay uncertainty estimates

- $h_i \to q\bar{q}$: SM-like: SM NNLO QCD, EW NNLO, SUSY 2L: $\sim 5\%$
  heavy: as SM-like, Sudakov logs: $\sim 5-10\%$

- $h_i \to \ell\bar{\ell}$: SM-like: $\lesssim 1\%$
  heavy: Sudakov logs for very heavy Higgses $\lesssim 10\%$

- $h_i \to WW^{(*)}, ZZ^{(*)}$: SM-like: $\lesssim 1\%$
  heavy: missing 2L (very small width): $\lesssim 50\%$

- $h_i \to \gamma\gamma, gg, \gamma Z$: $\gamma\gamma$: NNLO QCD, EW: $\lesssim 4\%$
  gg: NNLO QCD, EW: $\lesssim 4\%$
  γZ: NLO: $\sim 5\%$

- $h_i \to$ SUSY SUSY: [*S.H., C. Schappacher '14-'16*]
  1L effects $10-20\%$, 2L?

- all decays: $\mathbf{U}_{ij}$, $\mathbf{Z}_{ij}$: few %, effects close to threshold?

$\Rightarrow$ approaching LC precision for SM-like Higgs (not for heavy Higgses yet)

5. Conclusinos

- High precision prediction for cross sections and branching ratios are crucial for coupling constant determination
- Prediction (SM, MSSM, BMSSM) needed at/below the percent level!
- SUSY Higgs boson masses:
  - hybrid approach is best ⇒ FeynHiggs
  - MSSM: uncertainty in M_h reduced to 1-2 GeV
    (in simple single-scale scenario)
  - NMSSM: uncertainties intrisically larger, not calculaded
- MSSM Higgs production cross sections:
  Now available in the cMSSM at the full one-loop level:
  $$\sigma(e^+e^- \to h_i h_j),\ \sigma(e^+e^- \to h_i Z),\ \sigma(e^+e^- \to h_i \gamma)$$
  $$\sigma(e^+e^- \to H^+H^-),\ \sigma(e^+e^- \to H^\pm W^\mp)$$
  - Tree-level procs: loop corrections crucial $(e^+e- \to h_1 h_2, h_1 Z, \ldots, H^+H^-)$
  - Loop induced procs: possibly observable $(e^+e^- \to h_1 h_1, h_1\gamma, \ldots, H^\pm W^\mp)$

  ⇒ polarization could be crucial!

  ⇒ possibly relevant MSSM parameter dependence
- (N)MSSM Higgs decays:
  approaching LC precision for SM-like Higgs (not for heavy Higgses yet)


Further Questions?

Charged MSSM Higgs Production at the LC

Charged Higgs production:

$$e^+e^- \to H^+H^-,\ H^\pm W^\mp,\ H^\pm e^\mp \nu,\ H^\pm tb, \ldots$$

Now available in the cMSSM at the full one-loop level:
[*S.H., C. Schappacher '17*]

$$\sigma(e^+e^- \to H^+H^-)$$
$$\sigma(e^+e^- \to H^\pm W^\mp)$$

In the following:
few examples of each process, relevance of loop corrections

cMSSM parameters:

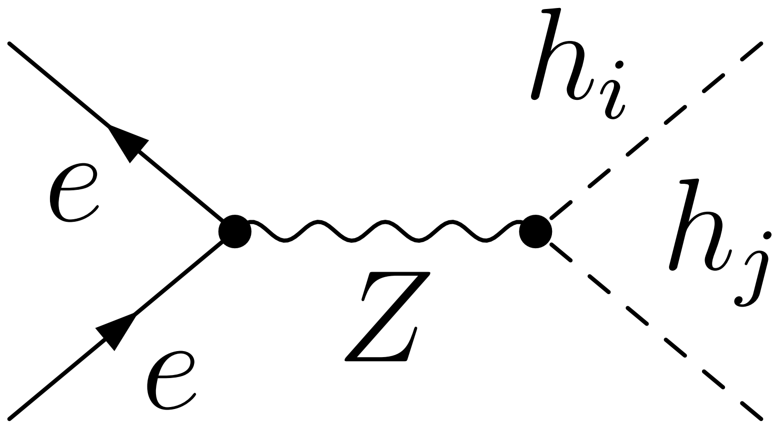
Table 1: MSSM default parameters for the numerical investigation; all parameters (except of t_β) are in GeV. The values for the trilinear sfermion Higgs couplings, $A_{t,b,\tau}$ are chosen such that charge- and/or color-breaking minima are avoided [64], and $A_{b,\tau}$ are chosen to be real. It should be noted that for the first and second generation of sfermions we chose instead $A_f = 0$, $M_{\tilde{Q},\tilde{U},\tilde{D}} = 1500$ GeV and $M_{\tilde{L},\tilde{E}} = 500$ GeV.

Scen.	$\sqrt{s}$	t_β	μ	$M_{H^\pm}$	$M_{\tilde{Q},\tilde{U},\tilde{D}}$	$M_{\tilde{L},\tilde{E}}$	$\lvert A_{t,b,\tau}\rvert$	M_1	M_2	M_3
S1	1000	7	200	300	1000	500	$1500 + \mu/t_\beta$	100	200	1500
S2	800	4	200	300	1000	500	$1500 + \mu/t_\beta$	100	200	1500

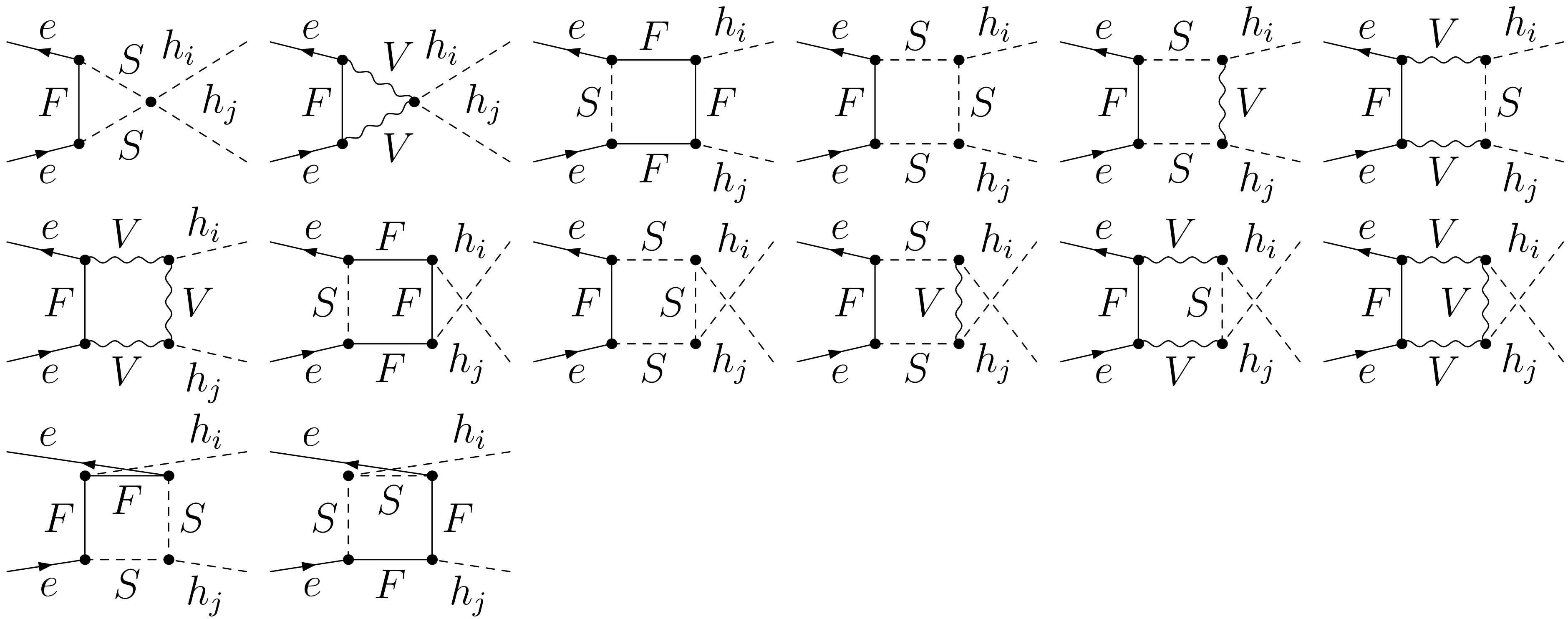
with $\sqrt{s}$, $M_{H^\pm}$, $\tan\beta$, ϕ_{A_t} varied

– Scenario chosen such that many processes are possible at the same time
– not chosen to maximize loop corrections

$e^+e^- \to H^+H^-$:



e
e
Z
h_i
h_j



e F S S e h_i h_j
e F V V e h_i h_j
e F S F F e h_i h_j
e S F S S e h_i h_j
e S F V S e h_i h_j
e V F S V e h_i h_j
e V F V V e h_i h_j
e F S F F e h_i h_j
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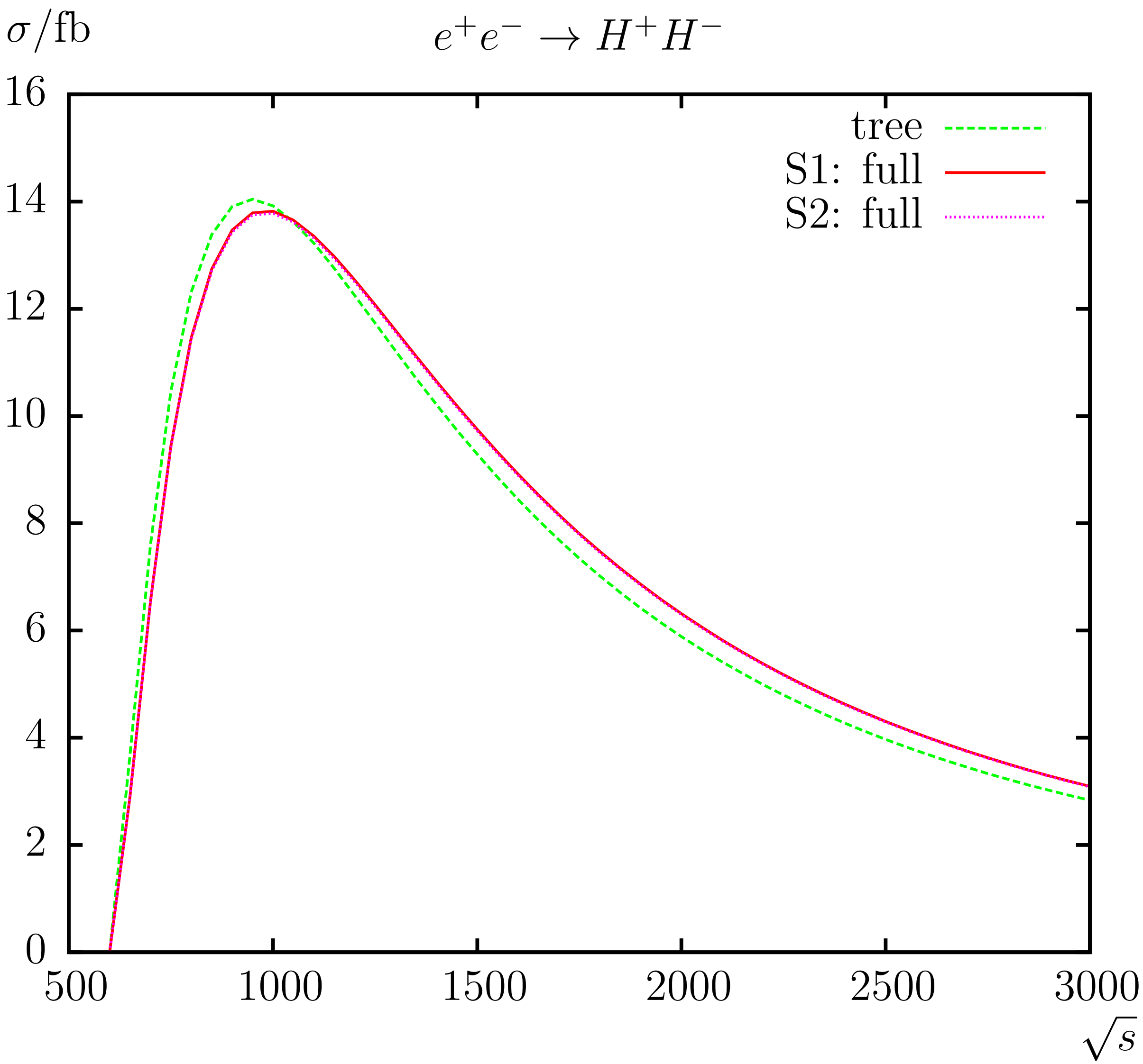
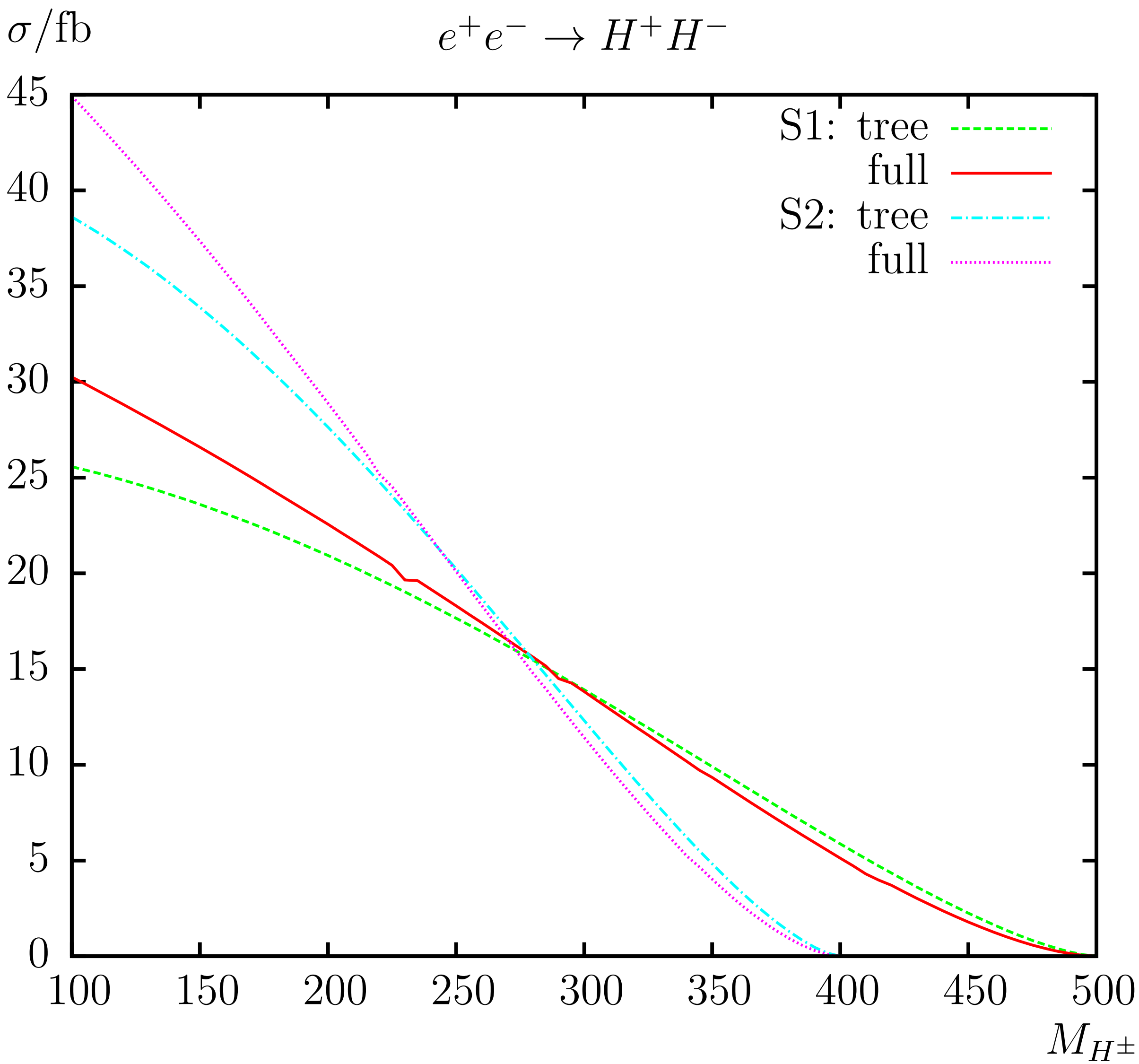


$\Rightarrow$ loop corrections non-negligible!

$e^+e^- \to H^+H^-$:



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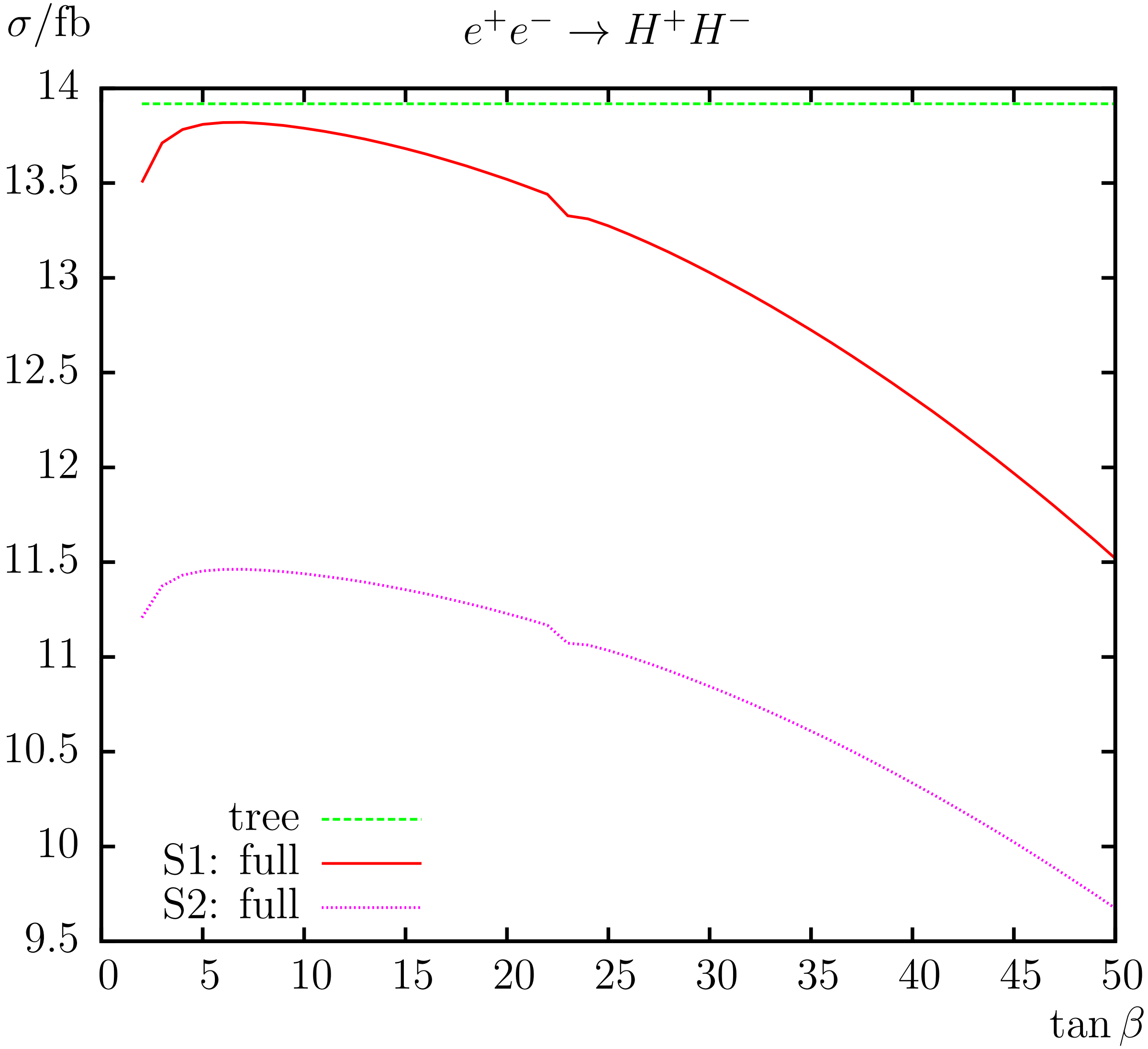
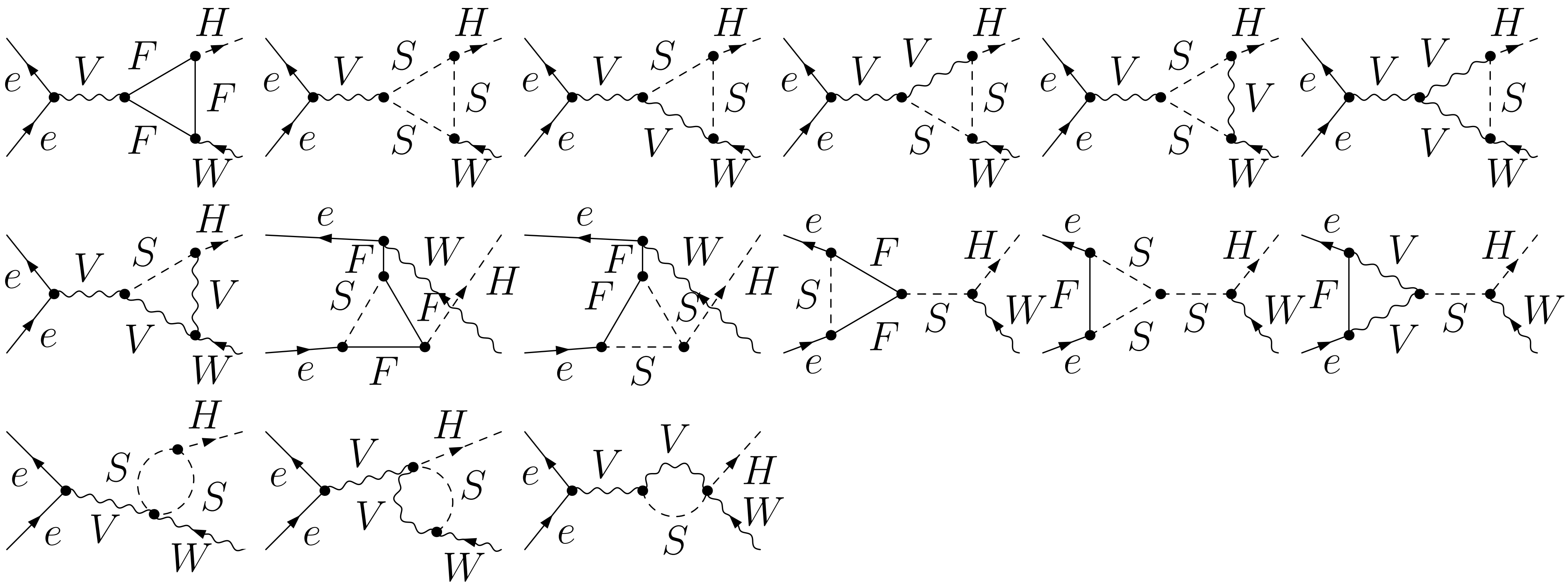


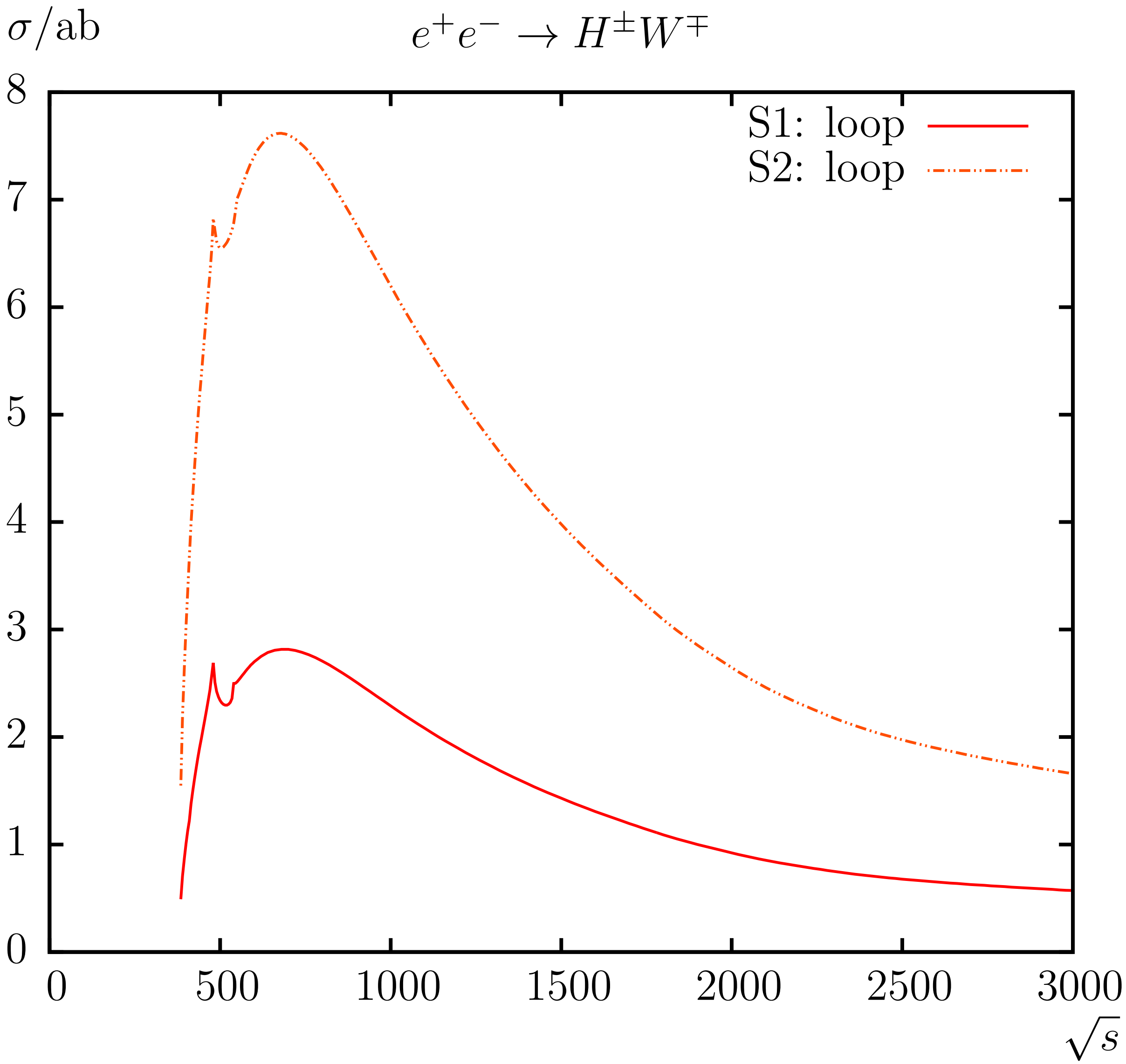
$\Rightarrow$ loop corrections sizable for large $\tan\beta$

$\Rightarrow$ no relevant complex phase dependence

$e^+e^- \to H^\pm W^\mp$: purely loop-induced!

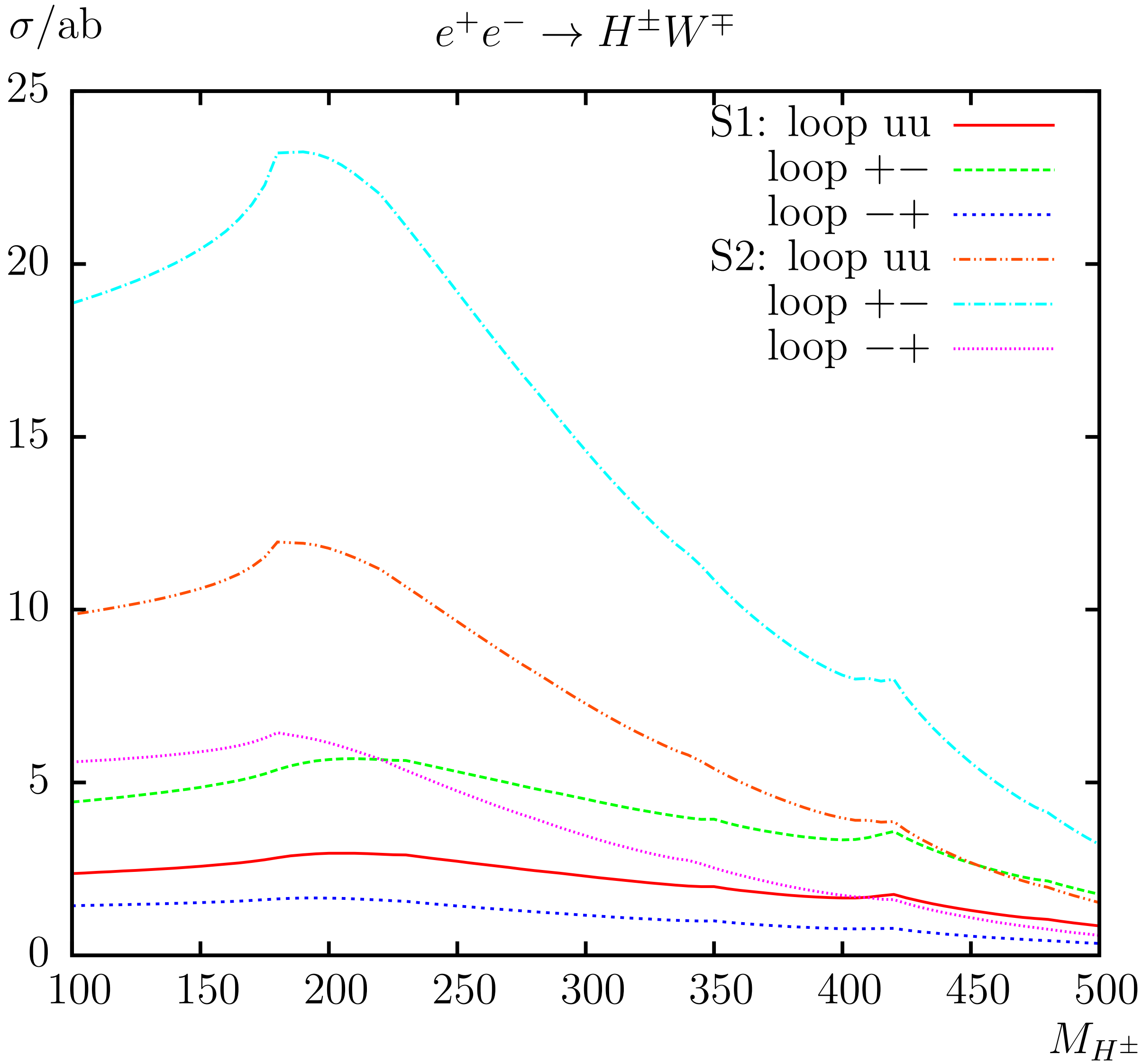


$e^+e^- \to H^\pm W^\mp$:



$\Rightarrow$ small loop-induced cross section . . .

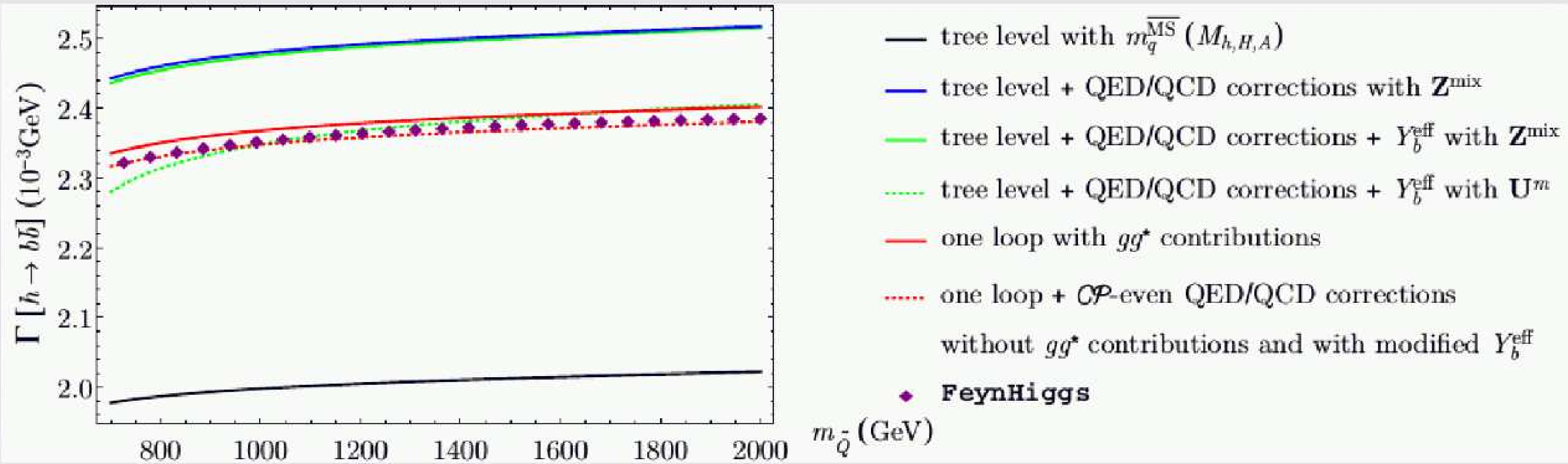
$e^+e^- \to H^\pm W^\mp$:



Polarization: $P(e^-) = +80\%$, $P(e^+) = -30\%$

$\Rightarrow$ crucial to yield detectable cross section!

[slide from F. Domingo]

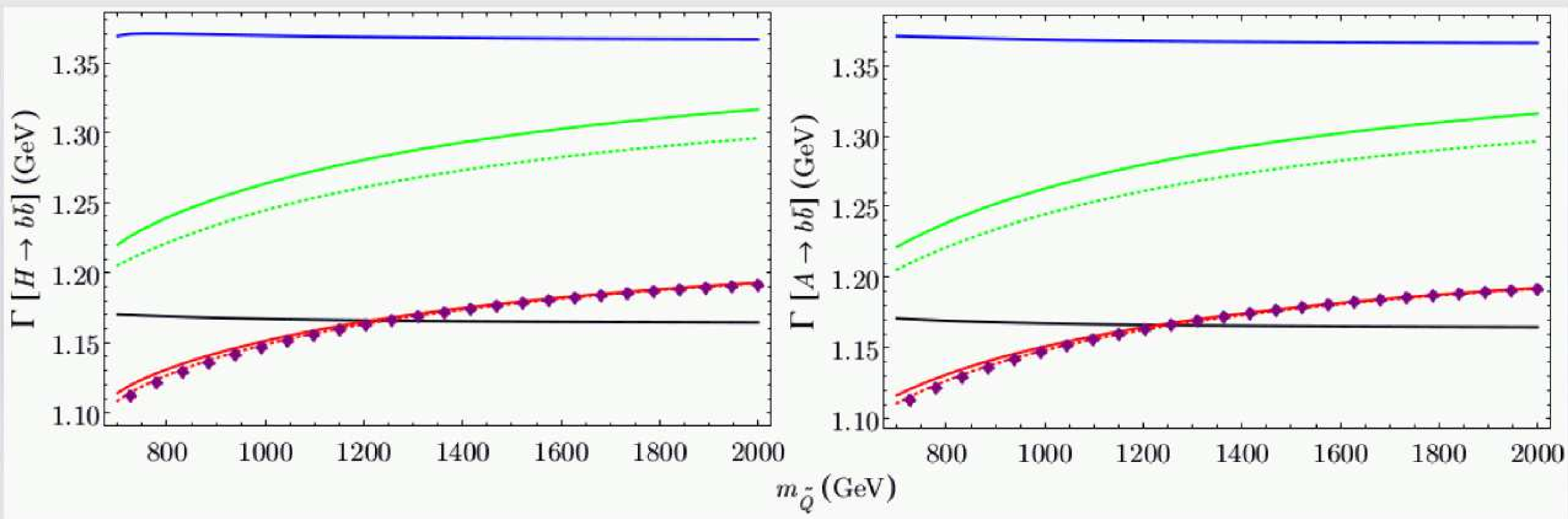


SM-like Higgs state

- Radiative corrections dominated by QCD-corrections;
- Unitary tree-level approximation works well;
- Difference wrt. FH (small): $h \to g(g^* \to b\bar{b})$ (whether $h \to b\bar{b}$ or $h \to gg$ is an experimental question).

Bringing the NMSSM to the same level: NMSSM in the MSSM limit

[*slide from F. Domingo*]

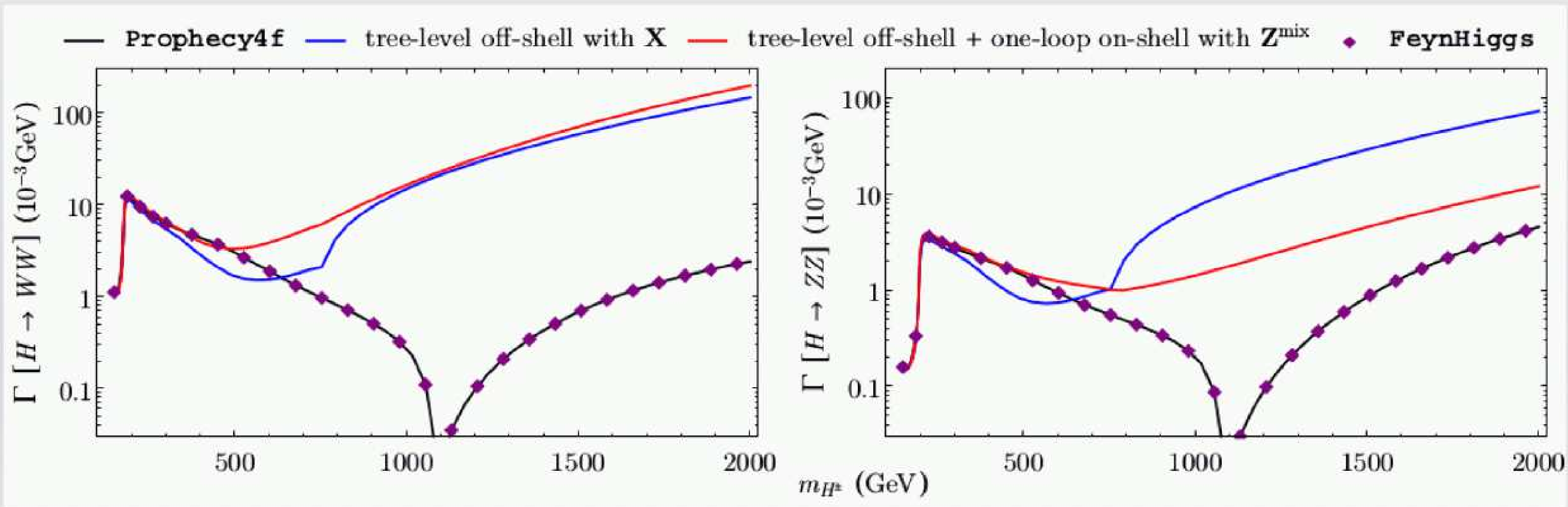


Heavy doublet Higgs states at $\sim$ 1 TeV

- Sizable EW corrections due to Sudakov logarithms;
- Unitary tree-level approximation 'fails' $\sim$ 10% off;
- Difference wrt. FH (minor): UV scale in Δ_b (higher-order).

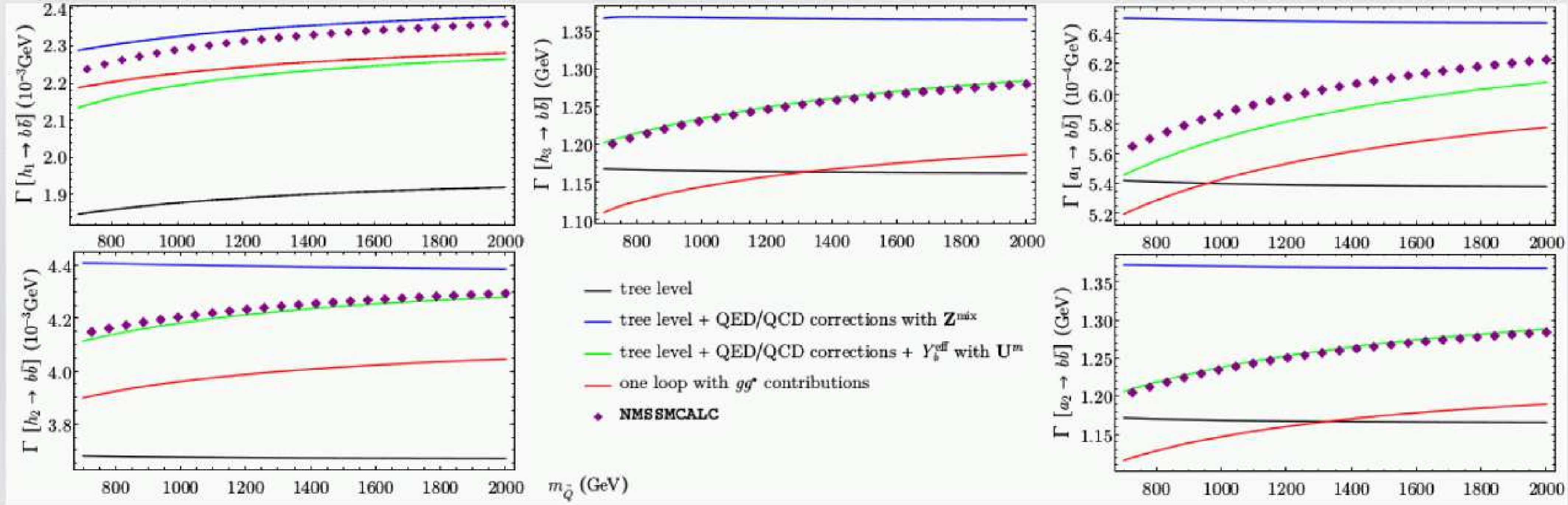
Bringing the NMSSM to the same level: NMSSM in the MSSM limit

[*slide from F. Domingo*]



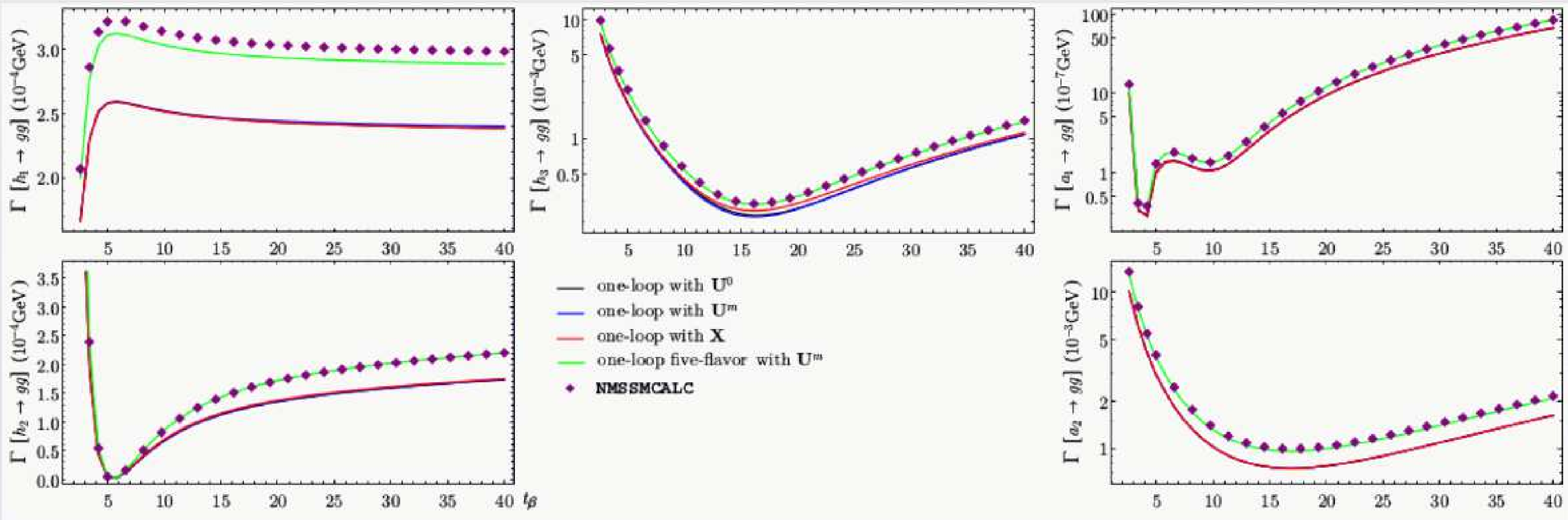
Heavy CP-even doublet Higgs state

- black curve: SM 1L prediction of Prophecy4f rescaled (as FH);
- Red curve: full one-loop (on-shell);
- Rescaling procedure fails for a decoupling state $g^{HVV}/g^{H_{\rm SM}VV} \simeq 0$.



- HDECAY provides a QCD/large $\tan\beta$-corrected width (including SQCD) $\simeq$ our green line;
- Full one-loop shows EW Sudakov logarithms for heavy states.

Here: h_1 SM-like; h_2 (640 GeV) and a_1 (320 GeV) singlet-like; h_3 and a_2 doublet-like (1 TeV).



- HDECAY performs at the same order as us with 5-flavor radiation;
- $\sim 4\%$ deviation due to normalization factor (difference of EW 2-loop and QCD 3-loop order).

Here: h_1 SM-like; h_2 (650 GeV) and a_1 (320 GeV) singlet-like; h_3 and a_2 doublet-like (1 TeV).